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U.S. INVESTMENT STRATEGIES for QUALITY ASSURANCE

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Report on

U.S. Investment Strategies for Quality Assurance

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Table of Contents

Executive Summary

American industry is currently under great pressure to respond to increasing global competition. There is little argument that part of the global competitive strategy for U.S. firms must involve improvements to the quality of their products. Despite the fact that quality is viewed as a critical component of a firm's competitive strategy, very little quantitative information exists regarding the character and magnitude of investment in quality assurance by U.S. industry. Furthermore, there is little information available of either a qualitative or a quantitative nature regarding the extent to which U.S. firms build their quality strategies around the availability of generic technologies, including measurement technologies supplied by public agencies. The recognition of the importance of quality investment (including measurement technology) and the lack of adequate information on the extent to which U.S. firms have invested in it formed the motivation for the National Institute of Standards and Technology (NIST) to undertake this study.

The study addresses the following issues.

- To what degree has quality become an increasingly important objective of American firms over the past decade?

- To what degree have quality investments become more pervasive throughout the R&D production and marketing chain?

- How important are measurement technology-related investments relative to the overall quality investments?

Collecting sufficient data to analyze these issues for U.S. industry in general would have been an impossible task simply because few companies have the data required to answer the questions in a readily accessible form. As a result, the study focused on two industries--optical fibers and semiconductors--in order to make the data-collection process manageable within available resources. These industries were chosen, in part, because of a judgment that both were making significant investments in quality in the face of international competition. Also, differences in the organization of the two industries, domestically and internationally, along with differences in production techniques provided an opportunity to address the issue of the influence of industry structure on the level and kind of quality investments.

The results obtained from formal surveys and interviews of executives in the two industries confirmed the view that a dramatic increase in the level of investment in quality assurance has taken place, including the use of measurement technology, over the past decade. The bulk of our information came from 35 companies in the optical fiber and semiconductor industries. Specifically, we found:

- both industries registered major increases in quality-related outlays over the past decade. Spending in the semiconductor industry for quality rose from about 10-20 percent of total outlays before 1985 to around 20-35 percent by the late-1980s. Firms in the optical fiber industry raised their spending on quality assurance from an estimated 13 percent of total outlays to an estimated 18 percent by the late-1980s.

- A significant component of the expansion in quality-related investments was spending on measurement technology-related investments. In both the optical fiber and the semiconductor industry, the evidence suggests that measurement-related outlays represent roughly 30 percent of total quality-related investments.

As investment in quality grew sharply, the objectives for the spending changed. Firms in both industries indicated that quality investments have become more important across a wide range of activities, including R&D production, marketing, and cost control. They affirmed the following points regarding their motivation for their investments in quality assurance from a business strategy viewpoint: Quality was increasingly achieved through product design as opposed to employing process technology; especially for mature products, production quality was achieved through modifying existing process technology; close coupling to users was essential; quality investments were essential in lowering production costs and gaining market share; and service quality is a increasingly key way to differentiate a producer in the marketplace. Note that firms in both of these high-technology industries stress refinement of existing concepts rather than breakthrough technologies.

Important differences between the two industries also emerged with regard to the nature and level of quality investments. At the most general level, for example, a majority of the firms interviewed in the semiconductor industry, unlike most optical fiber producers, reported that they no longer accepted the widely held definition of quality simply as fitness for use and conformance to specifications. A number of these

firms had evolved their philosophy on quality to embrace part, if not all of what Japanese managers call the **total management approach to quality assurance.** Furthermore, with respect to their objectives for quality investments, the semiconductor firms had more investments in quality focused on reducing product variability. The optical fiber firms tended to focus more of their quality investments toward improving manufacturability.

The differences in the approaches taken toward quality-related investments were created by the different competitive forces acting on the two industries. The U.S. semiconductor industry consists of a large number of niche producers along with a few broad line producers. Both types of firms confront a market where Japanese producers have set the pace with respect to technical quality. At the same time, the direction of the process technologies is not stable nor are there a small number of product attributes that can be used across all product families to measure quality. U.S. optical fiber producers, on the other hand, are few in number, dominate the U.S. and world markets, and focus their efforts on stabilizing quality in a high-volume production environment with relatively few key product attributes. These differences lead to a higher level of quality spending in the semiconductor industry spread across a larger number of activities, but a relatively lower investment in overhead outlays for quality.

In sum, we found that U.S. firms in both industries had clearly shifted the emphasis they place on quality investments, including measurement technology, over the past 10 years. While the two industries we examined in detail showed variations in the nature of their responses, the results from both industries affirmed that quality investments are an important strategic tool for U.S. businesses in competitive global markets. Our other important finding is that these two high-technology industries are basing their competitive strategies on evolutionary changes in a disciplined environment--not on expectations of dramatic technical breakthroughs. Underpinning this type of strategy is increasing investment in generic technologies such as measurement technology. We also found, although further study is required, that investments in measurement technologies were probably one of the fastest growing components of total R&D and capital investments over the past decade in these industries.

The change in the approach that these high-technology industries have taken to achieving competitiveness reflects a number of changes in the structure of these industries.

Customers are demanding quality--fitness for use and conformance to specifications--while at the same time technical processes are gradually stabilizing. This environment rewards disciplined organizations that can consistently produce high-quality products. In this setting, measurement technology becomes a critical input to the entire competitive process.

PART I

STUDY OVERVIEW AND SUMMARY OF KEY CONCLUSIONS

Chapter 1: Study Overview

American industry is currently under great pressure to respond to global competition. There is little argument that part of the global competitive strategy for U.S. firms must involve improvements to the quality of their products. This recognition of the importance of quality formed the motivation for the National Institute of Standards and Technology (NIST) to undertake a study focusing on investments in quality.

A. Objective of the Study

The objective of the study was to explore the degree to which quality is being integrated into the response of U.S. firms, relative to foreign competitors, to increasing world competition. Prior to this study, there had been no systematic analysis of investments in quality-assurance practices or measurement technologies by U.S. industries. What was known about quality-assurance practices in U.S. industries was largely based on anecdotal evidence and quite general in nature. This study refines and quantifies in detail the trends and strategies in investments in quality assurance and measurement technology.

We formulated three hypotheses regarding the importance of investments in quality to the production processes employed by U.S. firms.[1]

- Quality has become an increasingly important "input" to the activities of U.S. firms over the past decade.
- As quality investments become a larger proportion of overall economic activity, they also become more pervasive--i.e., more stages in corporate strategy incorporate quality assurance as a competitive objective.
- Measurement technology-related investments are a significant component of quality-related investments.[2]

This study explores the degree to which each of the hypotheses are borne out by U.S. firms. The actual level of importance that U.S. firms are according to quality is then compared to foreign competitors' use of quality as a competitive strategy.

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[1]Investment, for the purposes of measuring quality investment, was defined to cover both the investment in physical capital (plant and equipment), as well as on-going quality-related expenditures related to continuing operations.

[2]The initial project design identified the additional measurement technology issue of where and how specific measurement-related technologies have been applied. However, as the project progressed it became very clear that none of the firms providing data had the capability to carry their information to that level of specificity.

Investment strategies differ by company, by industry and even by country. The purpose of this study is to explore the trends and strategies in specific industries--across national boundaries where possible--with an eye toward how they may predict trends and strategies in quality investment in other industries. This study is also useful in shedding light on the degree to which industry characteristics--the number of firms, degree of globalization, standardization of the production process, and so forth--play a role in influencing the level and kind of quality-related investments.

B. Study Methodology

The majority of the work effort was concentrated on the information-gathering process--identifying and collecting data on quality-related investments. Given the magnitude and difficulty of the information-collection task, we focused on two industries: optical fibers and semiconductors.

B.1 Industry Selection[3]

The optical fiber industry and the semiconductor industry are both high-technology industries meaning, among other factors,

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[3]The selection of these two industries is detailed in Appendix G.

that their ratio of R&D to sales is above the average for most U.S. industries.[4] From NIST's point of view, this was an important characteristic for the industries in the study because R&D-intensive industries typically have a significant requirement to apply generic measurement technology at some or most phases of the manufacturing and marketing chain. By selecting two high-technology industries on which to focus the study, there was a reasonable expectation that measurement technology investments would be an important component of total quality-related investment outlays.

Another reason for selecting these two particular industries was that during the 1980s firms in both industries encountered an increasing degree of international competition. A detailed assessment of changes in quality-assurance investments in these two industries over the past decade would provide insight on the degree to which firms changed the level and kind of quality investment in response to growing international competition.

A third reason for selecting these two industries was the belief, later confirmed from the data we collected, that quality

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[4]Other characteristics of a high-technology industry are that the product technology is still fluid, that the base manufacturing technology has not matured, and that the level of engineering skills required to manage the overall operation is relatively high.

was likely to be an important cost and strategic element. There were several structural characteristics of these industries that *a priori* led us to conclude that quality was likely to be important. Among the more important reasons were the following:

- The output of both industries is a crucial intermediate input into a final system product. The input is crucial in the sense that the overall reliability of the final system is heavily influenced by the performance of either the optical fiber or the semiconductor component. The input is not however, a crucial cost element of the final system. Typically, the semiconductor content of a final system is between 5 and 15 percent, while the optical fiber content of a final system might be 5 to 10 percent. Note that though the cost share is relatively low, poor performance by this intermediate input would jeopardize the overall system-level performance. Thus, because the overall system performance is so heavily dependent on the performance of the intermediate input, the system-level integrators place a premium on the reliability and quality-assurance aspects of the intermediate input.

- Both the optical fiber and the semiconductor industries, relative to other volume-manufacturing industries, utilize complex and exacting manufacturing processes.[5] Command and control of these manufacturing processes have led the industries to integrate quality-assurance practices into their manufacturing management systems. Quality-assurance practices based only on final inspection of the completed product have proven to be inadequate.

- The base manufacturing technologies utilized by the optical fiber and semiconductor industries are changing due to evolutionary developments. That is, optical fiber technology is based on silica while semiconductor technology is based in silicon. Absent a major breakthrough in materials technology, firms in these two industries know

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[5] See Appendix A and Appendix C for a general discussion of the manufacturing processes of these two industries. Also, Chapter 9 discusses several aspects of the semiconductor manufacturing process indicating its complex nature.

that competitive advances can only be achieved through the gradual evolution of the base manufacturing technology. R&D in this type of operating environment interacts with quality assurance in a highly disciplined framework. That is, R&D is not done with the objective of seeking a radical new approach, but is undertaken as a means to foster quality improvements either within the manufacturing operation or in the perceptions of the customer base.

We also believed a priori that the U.S. semiconductor and optical fiber industries had higher-than-average investments in quality. We expected to gain insights into how the different organizational features of the two industries influenced their respective approaches toward quality investments. Finally, between these two industries, we felt there would be significant differences in the levels and types of investments resulting from variations in structural features between the two industries.

A comparison of structural features of the two industries allows us to develop a context for the key conclusions we present in the next chapter. Table 1 lists the major structural features of the optical fiber and the semiconductor industries that we believe influenced the findings we obtained from the surveys.

Table 1

Comparison of Optical Fiber and Semiconductor Industry Characteristics

	Optical Fiber	Semiconductors
Product diversity	Relatively homogeneous	Large number of product families
Number of firms		
-- Global industry	Fewer than 10 major players worldwide	More than 30 major players worldwide
-- U.S. Industry	Two major/five overall	15 major/200 overall
Economy of scope in manufacturing	Yes	Limited--concentrated in highest volume product families
Well defined technical roadmap[6]	Yes	Mainstream processes are stabilizing
Production process standardization	Limited variations on basic process	Process varies by type of product
Capital-intensive production process	Yes	Varies by type of product
U.S. technical lead	Yes	Not in all key technical areas
Global industry[7]	Yes	Yes
Importance of Raw Materials to Quality of End-Product	Direct Influence	Direct Influence

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[6]By technical roadmap we mean that there is understood direction and rate of change for the evolution of key manufacturing parameters.

[7]By global industry we mean that products are standardized worldwide and marketed worldwide by a common set of manufacturers.

To discuss each point noted in Table 1:

- The fact that optical fibers are a relatively homogeneous product simplifies the issue of stabilizing specifications that the customer can use to gauge the acceptability of the incoming product. It also simplifies the task of designing an organizational structure to achieve desired levels of performance. On the other hand, semiconductors are a diverse group of products. Specifications and customer requirements both vary. Investing in quality is a more difficult task since quality is not defined by a limited set of parameters that crosses all product families. This suggests that quality investments in the semiconductor industry, relative to the optical fiber industry, would be more diffused throughout the line organizations. It also suggests that a relatively greater investment in quality is required since there are more aspects of the manufacturing operation that need attention in order to achieve desirable levels of quality.

- The larger number of firms in the semiconductor industry reflects, in part, the fact that the existence of product market niches lowers the entry barriers into the overall business of semiconductor manufacturing. In this setting, quality investments play several roles. They provide a way to differentiate a firm in the market or, in commodity markets, they insure that the firm neutralizes a competitor's quality advantage. The measurement component of quality becomes important due to the need to work out standards even as the technology continues to evolve. In the optical fiber industry, the small number of firms combined with a homogeneous product (and a relatively stable production technology) makes it difficult for firms to differentiate themselves in the market using quality investments. Overall, the influence of the number of firms (and the underlying economics implied regarding firm entry/exit costs, etc.) is to increase the relative spending on quality assurance, including measurement investments, in the semiconductor industry relative to the optical fiber industry.

- Economies of scope have an ambiguous influence over the relative level of quality investments in the two industries. If quality investments are a deterrent to entry, then one might expect them to be relatively higher in the optical fiber industry to capture scope effects. If however,

quality investments are not a barrier to entry because the underlying know-how is rapidly diffused to all participants, then quality investments could be relatively higher in the semiconductor industry.

- The issue of a well-defined technical roadmap ties back to the point regarding economies of scope. To the degree that technical developments are orderly, well anticipated, and easily diffused to all participants, there would be less investment in quality assurance. The semiconductor industry is characterized by factors that tend to raise investments in quality assurance--the continual need to revise old standards, define new standards, control process evolution, etc.

- The production process in semiconductors ranges from straightforward to extremely difficult depending on the type of product. For optical fibers, the variations of the production process are more limited. Where the production process is more standardized, there are fewer points at which to apply quality-related metrics. Fewer points of application suggest a relatively lower level of quality-related investments.

- The capital intensity of the production process may not directly influence the overall level of quality investments, but it should influence where firms make the investments. Specifically, quality-assurance investments should be higher in capital and operations budgets relative to the R&D and overhead budgets. That is, the more capital intensive the manufacturing process is, the more firms would be integrating quality-assurance techniques directly into those operations. Both industries we studied were capital-intensive, thus this factor would not discriminate.[8]

- The U.S. optical fiber industry is a technological world leader whereas the U.S. semiconductor industry no longer is leading in all major fields of semiconductor technology. In particular, as we document in detail in Chapter 9, the U.S. semiconductor industry had to adopt a number of policies of the Japanese semiconductor firms to catch up with the Japanese firms in the 1980s. The Japanese semiconductor

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[8]The larger semiconductor firms that provided much of our data are likely to engage in capital-intensive manufacturing approaches since they produce commodity or high-volume product families.

industry effectively used quality as a strategic market tool to capture market position. American firms competing in the same markets had to match the Japanese levels of quality investment or simply drop out of the market--as many did.

- Both industries are global in their scope. But there is a difference. In the semiconductor industry, larger firms, that are global in scope, use their ability to provide global customer support functions (including an emphasis on customer service quality) as a means to discriminate their product offerings from smaller firms that lack the global reach. This strategic use of quality would increase quality investments relative to the optical fiber industry, where all the major U.S. players are global in their market reach.

- Raw material inputs have a significant influence on the quality of the end product. These materials have a very specific set of quality-related characteristics that can be measured. In both industries, the trend is to make the suppliers invest in the measurement-related technologies to guarantee the quality level.

B.2 Data Collection

Having identified the industries on which to focus, the issue became what was the best means to collect information. In our proposal to NBS/NIST[9] discussing our methodology for this study, we anticipated that developing the necessary data to test the three hypotheses regarding the importance of quality and measurement investments would be difficult. As we stated:

"To date...there is little quantitative information regarding the character and the extent of adoption of QA&PC [quality assurance and process control] by U.S. industry, or

[9] In 1988, the National Bureau of Standards (NBS) became the National Institute of Standards and Technology (NIST).

of the measurement component of QA&PC. Furthermore, there is insufficient qualitative or quantitative information regarding the extent to which our domestic companies have taken advantage of the generic technologies available to them, including the measurement technologies offered by NBS."[10]

We decided to use a mixture of questionnaires and interviews. The questionnaires were used to develop a framework. Due to the fact that few firms actually kept data on quality investments defined in ways that would be useful for our purposes, we decided to interview a large number of cooperating firms to confirm the survey responses and obtain elaborations on the data they submitted.

From the U.S. optical fiber industry, we received information from all five companies that received a questionnaire: three responses to the full questionnaire and two responses to a shorter version of the same questionnaire. Seven foreign firms also responded to our request for information on quality investments in optical fibers.

The bulk of our information on quality investments in the semiconductor industry came from seven detailed interviews. Four

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[10] See Quick, Finan & Associates (QFA) proposal to the National Bureau of Standards, Reference: Costs of Measurement in Quality Assurance and Process Control, February 17, 1988, pp. 3-4.

other semiconductor firms responded to our survey and nine firms responded to the separate survey on measurement technologies.

C. Overview of the Study

This is a benchmark study on investments in quality and measurement technologies. We systematically collected information on quality-assurance practices in two important U.S. industries for the first time. We are the first to study in depth the strategic role that investments in quality play in the global competitiveness of U.S. industries. Because the study is unique, we have provided a great deal of detail in this report as full documentation of the findings and conclusions.

The essential findings and conclusions are fully presented in the next chapter--Chapter 2.

The reader who wants detailed presentation and analysis of the data collected during the course of this study should read Parts II and III of this report. Part II details quality-assurance practices in the optical fiber industry. Chapter 3 (the first chapter in Part II) focuses on the domestic optical fiber industry and covers the surveys and interviews conducted for this study. A comparison between U.S. and foreign approaches to quality assurance (QA) in the industry is drawn in Chapter 4.

Part III (Chapters 5 through 9) of this study focuses on the semiconductor industry. Chapter 5 provides an overview of the analysis presented in this part. In Chapter 6, the survey and interviews related to investments in quality within the U.S. semiconductor industry are analyzed in detail. A separate analysis of the survey results on measurement-related investments is in Chapter 7. Chapter 8 ties together the results and analysis of the two surveys of the domestic semiconductor industry. Chapter 9 then takes the findings from the U.S. industry and compares them with the approach to quality used in the Japanese semiconductor industry.

The appendices provide additional documentation and detail on this study. Appendix A is an overview of the optical fiber industry. The survey used to collect information on quality investments in the optical fiber industry is given in Appendix B. Appendix C is an overview of the semiconductor industry. In Appendices D and E are the semiconductor surveys on investments in quality and measurement technologies respectively. A glossary of quality terminology used in this study is contained in Appendix F. Appendix G provides additional detail on the selection of industries for the study.

Chapter 2: Summary of Major Conclusions of the Study

This chapter summarizes the key findings of our assessment of quality-assurance investments in the optical fiber and the semiconductor industries. The conclusions are presented according to the three major issues addressed in this study: the relative importance of quality as an objective of American firms; the role of quality investments in competitiveness; and the importance of measurement investment (and NIST support of it) in the context of quality improvements. The second section provides a general comparison of our findings for the optical fiber and semiconductor industries.

A. Summary of Major Conclusions

A.1 Importance of Quality

There are two issues related to the importance of quality. First, is the definition of quality used by the firms covered in this study. The second issue is, given a firm's definition of quality, what the trends in quality-related expenditures are relative to the total budget.

Definition of Quality: Has It Changed?

There were two reasons to examine whether or not the firm's surveyed for this study had changed their definition of (or philosophic approach to) quality. First, in the context of conducting the survey, we needed to know if respondents were basing their answers on a common understanding of what constituted an investment in quality assurance. Second, responses to the question shed light on the issue of how firms perceived the evolution of their strategies in a globally competitive marketplace. Most of the semiconductor firms clearly saw the structure and demands of the world market changing and, in turn, requiring a strategic competitive response. Their customers were educated by the Japanese suppliers about a new level of quality performance, and the American semiconductor firms had to effectively respond or simply disappear as viable competitors. Their definitions of quality tended to reflect this competitive imperative. On the other hand, the U.S. optical fiber firms had not fallen behind their international competitors and therefore accepted a narrower view of the definition.

Summarizing our findings on this point:

- Four of the five U.S. optical fiber producers accepted in an unqualified fashion the definition of quality as conformance to specifications and fitness for use.

- Among U.S. semiconductor firms designated leading-edge quality-control (QC) firms, the concept that quality is conformance to specifications and fitness for use is no longer accepted as the appropriate definition. This reflects a change in quality-assurance strategies over the past decade. Up through the early-1980s, most U.S. semiconductor firms relied principally on inspection and verification methods to insure quality. There has been a significant shift in the quality philosophies of the U.S. semiconductor firms in the last five years. All the U.S. semiconductor firms interviewed indicated that they are applying part, if not all, of the key aspects of the Japanese total management approach to quality-assurance strategy.

<u>Trends in Overall Quality-Related Expenditures</u>

- Based on the survey responses received from the U.S. semiconductor companies, we estimate that roughly 20 to 35 percent of the total budget of U.S. semiconductor companies was devoted to achieving acceptable levels of quality. For the industry as a whole, that translated into $3.7 to $6.5 billion. Total quality-related outlays in the semiconductor industry in absolute terms increased four-fold over the past decade--an annual rate of increase averaging 15 percent. In relative terms, quality-related semiconductor investments have grown more than the rate of growth of the industry overall and faster than investment in R&D or capital expenditures for equipment and structures.

- For the U.S. optical fiber producers, based on discussions with several industry experts and survey respondents (in a Delphi manner), annual expenditures toward achieving quality by all firms in the industry increased from an average of 13 percent of their total budget in 1980-1985 to an average of 18 percent in 1988-1989. This percentage corresponds to a

current annual investment in quality assurance in the U.S. optical fiber industry of at least $25 million, or about 9 percent of total industry sales (1987 value of shipments were $268 million).

- Comparing U.S. and international firms in the optical fiber industry, two conclusions were reached:

  -- U.S. firms, compared to international firms, allocate a larger percentage of their budgets toward quality assurance, in general, and toward measurement, in particular. For the international firms, allocations toward quality increased from an average of 7 percent of total budget in 1980-1985 to an average of 12 percent in 1988-1989--compared to the averages of 13 and 18 percent for U.S. firms in the same two periods, respectively. This fact may, in part, account for why U.S. producers have a significantly larger share of the world market.

  -- Both U.S. and international firms producing optical fibers appear to be investing to build quality into their overall production process as opposed to achieving quality solely through new product technology.

A.2 The Role of Quality Investments in Competitiveness

The two major issues on quality investments were the role of quality assurance as a strategic competitive tool by firms and the implementation of that strategy as reflected in the distribution of quality-related expenditures by functional category.

Findings on the Role of Quality Assurance as a Strategic Tool

Surveyed firms in the two industries generally affirmed the following viewpoints regarding the role of quality assurance as a strategic tool:

- Quality is increasingly achieved through product design rather than new production technology.
- Production quality for mature products is increasingly achieved through simply modifying existing technology, rather than through distinctly new technology.
- An important component of quality improvement is user feedback provided by marketing/sales personnel.
- Improving product and process quality is a strategic option for gaining market share.
- Quality is an essential element of cost-reduction strategies.
- Service quality is now a key differentiating factor among vendors.

Findings on the Implementation of the Quality Strategy

For the U.S. semiconductor producers, our assessment notes the following points regarding implementation of the quality strategy:

- In parallel with the increased outlays for quality investments, there has been a major shift in the quality-assurance practices of the U.S. semiconductor firms over the past decade.

  -- First, there has been a shift toward spending more dollars on prevention in operations, R&D, and capital budgets relative to spending on inspection and detection. The share of total quality-related expenditures being invested in prevention more than doubled from the early-1980s to 1988. At the same time, outlays related to appraisal and internal and external failures declined--perhaps being cut nearly in half.

  -- Second, the nature of quality- and prevention-related expenditures shifted in favor of nontechnology expenditures, covering control (including SPC), improvement (including training programs), and management (quality engineering and quality control).

  -- Third, the relative importance of various objectives for quality outlays has changed from improving product performance and manufacturability to reducing variability of the product attributes, increasing product reliability, and reducing the cost of test and QA. This shift is the operational outcome of the broader trend favoring nontechnology expenditures as the means to achieve quality improvement.

- Additional points regarding how the semiconductor industry tactically approaches quality assurance:

  -- "Quality is emphasized through the team concept with customer representatives involved at all stages of production and planning, especially in R&D."[11]

  -- In the LSI era in order to monitor the process variables during wafer processing, roughly 100 database records would be required to track each lot or batch of

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[11]"The military community is not driving QC. The automotive industry is the single largest most aggressive QC driver followed by IBM...Currently, the requirements for the auto industry are driving the leading edge of the commercial industry base [for quality-assurance practices.]" Source: Survey interviews.

wafers. This grew 50-fold in the VLSI era and today is expected to be 100-fold greater in the ULSI era. Thus, quality assurance in the ULSI era simply could not be accomplished with the same management methods that were viable for the LSI era of semiconductor technology. In the past, these controls were based on statistical process control (SPC) methods, but in the ULSI era, the semiconductor producers worldwide, with the Japanese producers taking the lead, have found that previously applied SPC methods are not adequate.[12] The pressures of dealing with more and more complex processes, yet still sustaining high yields in production, impacted the way Japanese managements dealt with the problems of quality assurance. American managements have been faced with the dual problem of confronting the pressures of more and more complex processes while at the same time effectively addressing the market pressures created by Japanese competition.

A separate issue addressed in the study was how the competitive challenge posed by Japanese semiconductor firms affected the implementation of general business strategies by the American firms.

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[12]For example, in the manufacturing environment for high-density integrated circuits of the early- to mid-1980s, the overwhelming sources of particulate contamination during wafer processing were people and the general ambient conditions of the clean rooms in which wafer processing took place. Throughout the 1980s, these two sources of particulates grew to be less and less important. Today, the principal sources of contamination are the equipment and the materials. Japanese semiconductor firms were at the forefront of recognizing the implications of the changes. A Japanese semiconductor executive noted: "Semiconductor production is extremely dependent on the quality of equipment. The quality of the finished wafer is, therefore, directly linked to the quality of the production equipment." Likewise, with respect to materials, Japanese device companies began setting goals for impurities and delivery conditions that placed significant pressure on vendors to excel.

- Among the set of American semiconductor firms that we call leading-edge practitioners of quality, it is difficult to discern major differences in general quality policies or even in key techniques used to implement their quality strategies relative to their major Japanese competitors.

- Among the areas where external relationships in Japan have led to differences in quality-assurance practices, two are especially important to understand in detail: (1) extensive feedback of quality-assurance data from customer to semiconductor vendor (and its application by the vendor to resolve the problem); and (2) close coupling between device producer and equipment and material vendors in Japan.

- Two aspects of the Japanese semiconductor producers' relationships with their material vendors that have an especially important influence on quality are, first, the process of joint development of specifications and, second, the ongoing, continuous monitoring of actual performance.

- Japanese firms are considered, even by U.S. managers, to have a greater degree of discipline within their organizations. Greater discipline means, for example, tighter control over process specifications and closer coupling between design engineers and process engineers to ensure a product's design will optimize the process (i.e., yield and product performance) being run in the fab.

For the U.S. optical fiber producers, we found the following regarding implementation of the quality strategy:

- The following table summarizes the current estimated distribution of quality outlays by budget objective for the optical fiber industry. The distribution indicates a very different emphasis across the various objectives relative to the findings for the semiconductor industry. For example, in the semiconductor case, greater emphasis was placed on reducing product variability relative to improving product performance.

Objective	Percentage of Quality Budget
Improving Product Performance	28
Reducing Attribute Variability	15
Increasing Product Reliability	17
Decreasing Need for Serviceability	5
Increasing Product Life	5
Improving Manufacturability (Includes improved materials and processes)	31
Other	4
TOTAL	100

- Relative to international optical fiber firms, U.S. firms expend a larger portion of their resources on quality-related investments. The following table compares international and U.S. optical fiber firms' outlays across major budget categories. In every instance, the U.S. firms allocated, on average, a greater percentage of budget toward achieving quality. The similar allocation pattern between the international firms and the U.S. firms is noteworthy. A relatively greater percentage of capital and R&D budgets is allocated toward quality than of the operations and overhead budgets. This pattern is consistent with the observation of quality being built into the production process.

Budget Category	Avg. Int'l Percentage	Avg. U.S. Percentage
Operations	4	19
Capital	6	27
R&D	9	27
Overhead	5	22

A.3 The Importance of Measurement Investments

The two major issues related to measurement investments were the trend in those investments and NIST's role in supporting measurement investments in the optical fiber and the semiconductor industries.

Trends in Measurement Investments

- Given that the responding semiconductor firms indicated that currently between 20 and 35 percent of their total budget is allocated toward achieving quality, this suggests that between 3 and 14 percent of the total outlays of the semiconductor industry is allocated toward measurement technology. In terms of 1988 budget outlays for the industry, this would imply that between $560 million and $2.6 billion is invested annually by the semiconductor industry in measurement technologies that support quality.

- For the optical fiber industry, approximately 27.5 percent of U.S. firms' total budget for quality is allocated toward measurement. Using the estimate that total industry expenditures toward achieving quality are between $25 and $30 million, then a reasonable estimate is that between $7 and $8.3 million is devoted toward measurement expenditures.

Importance of NIST's Role

The following views were noted in the survey responses regarding NIST's role in supporting quality and measurement-related investments:

- In the semiconductor companies, the personnel involved in the quality-related programs who responded to the QA-related survey questions were frequently unfamiliar with specific aspects of investments related to measurement technology and the degree and type of involvement of their firm with NIST. Typically, those who were familiar were situated in a different part of the organization, either in direct measurement-related activities (measurement lab for example) or in an R&D-related segment of the organization. A separate survey on measurement technology and NIST support of measurement activities produced a very different set of responses.

- With respect to the optical fiber industry, the responses suggest that NIST has been a valuable source of quality-related information, used by a majority of firms in the U.S. industry.

It is not clear why there was such a divergence between the views of the two industries, but there are several factors that may be at work in these responses. One factor relates to product maturity. The semiconductor industry is a more mature industry than the fiber optic industry. Optical fiber standards evolved in the early- to mid-1980s, whereas the semiconductor industry used NIST (then NBS) assistance with measurement-related standards much earlier. Another factor is the size of the industry. NIST spends about 30 percent as much as the optical fiber industry but less than 0.5 percent as much as the semiconductor industry.

B. Comparison of Findings Between the Optical Fiber and the Semiconductor Industries

Based on the survey results from the two industries, several general observations emerge. It is clear that in both industries quality investments are becoming more pervasive throughout the production process. Firms see quality investments as important not only in terms of improvement of the end-product, but as a tool to reduce manufacturing costs, a means to improve market share, and an aid to shorten time to market.

Improved manufacturability was receiving less direct QA investments; firms were applying nontechnology-based management techniques to refine various aspects of manufacturing practices in order to reduce product variability and increase product reliability. But our evidence also supports the conclusion that quality has become a competitive tool that is more persuasively applied beyond just the manufacturing arena. Thus, the diffusion of quality-assurance investments spilled over beyond the traditional narrow confines of the manufacturing floor into marketing and R&D.

There was one striking difference that emerged between the U.S. and Japanese semiconductor industries in how their managements viewed quality investments. American semiconductor

managers had their entire strategic orientation toward quality assurance shaped by their perceptions of what their Japanese competitors were doing. This external influence was not nearly as evident in the case of the optical fiber producers. Japanese semiconductor firms throughout the 1980s had been considered the leaders in establishing world-class quality. American semiconductor managements sought to understand and emulate how the Japanese semiconductor firms were able to achieve high and stable levels of quality.

Among the other key findings we make on this point are the following:

- In both Japan and the United States, there are a number of "background" or infrastructure activities that support and encourage improvements in quality-assurance practices. One difference, however, is that there may be a larger number of these organizations in Japan. Due to the nature of Japanese corporate culture, it may be easier to change corporate practices (in the direction of achieving improved quality) through the use of the various support organizations.

- Structural differences between the Japanese and the U.S. industries such as quality driving end-markets and major product groups driving technical improvements, created problems for the U.S. efforts to move toward world-class quality levels.

- The Japanese integration of quality into the business strategy influenced both the organization of their businesses and also their management style. The implementation of that strategy tended to focus in three areas: line operator training, automation of production lines, and improvements in equipment. External relationships with equipment and materials firms also

facilitated achieving higher quality-assurance goals. More extensive feedback of quality-assurance data between vendor and customer and greater exchange of information on product requirements and specifications were two aspects of the external relationships in the Japanese industry that were qualitatively different from those in the U.S. semiconductor industry.

- The Japanese semiconductor firms are still widely viewed as being at the forefront of quality-assurance practices. But the evidence suggests that there has been a major closure--if not elimination in certain cases--of the differences in quality levels by American semiconductor firms. The evidence developed for this report suggests that among leading-edge practitioners of quality-assurance strategies in both countries, the differences in design of the overall strategy are not that large. Firms in both countries define their quality strategies differently from the classic definition of quality that focuses only on the concept of "fitness for use." Where differences are still evident is in the techniques used to implement quality-assurance strategies.

PART II

ANALYSIS OF INVESTMENTS IN QUALITY ASSURANCE AND MEASUREMENT TECHNOLOGY IN THE U.S. OPTICAL FIBER INDUSTRY

Chapter 3: Investments in Quality Assurance in the U.S. Optical Fiber Industry

A. Overview of Data Collection

Information on QA-related investments was provided by the five major producers of optical fiber. While there are some small producers in the United States that make fiber as only one part of their final integrated product, this sample of five firms constitutes, for all practical purposes, the entire U.S. optical fiber industry.[13] These five companies are AT&T, Alcatel, Corning, Spectran, and Sumitomo Electric.[14]

Two survey instruments were prepared for this part of the study. A lengthy detailed instrument was developed and administered to AT&T, Corning and Alcatel--the dominant producers

[13] See Appendix A for a general description of the optical fiber industry.

[14] Sumitomo Electric stopped producing fiber in February 1989. However, we were able to obtain data on their previous year's activities. Now, fiber is produced by LITESPEC, a joint venture between Sumitomo Electric Industry of Japan and AT&T.

in the U.S.[15] A shorter version was prepared and administered to the two smaller companies. This shorter version contains a subset of the questions from the longer version.

Our a priori belief was that the smaller companies would be more reluctant to participate in this study. It was thought that an abbreviated instrument would maximize our response rate. Also, it was believed that NIST's contacts with representatives at both AT&T, Corning and Alcatel would allow us to obtain more detailed information than otherwise possible.

It was extremely difficult and time consuming to obtain responses from the firms. This is probably due more to the fact that few firms have a system to account for investments in quality than due to lack of interest in the study. Throughout the process of data collection, one trend became apparent--no one person within a company could complete all aspects of the instrument. This was probably due to the complexity of the subject and lack of established accounting practices rather to any ambiguities in the instrument.

The discussion in Sections B, C and D of this chapter is related only to the common questions contained in both surveys.

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[15]For a copy of the survey see Appendix B.

One of the common survey issues was the utilization of NIST as a source of quality-related information to the optical fiber industry. The responses regarding NIST are separated from the other responses and analysis in Section D. Section E reports some general trends on quality as a strategic tool from the AT&T, Corning, and Alcatel responses to the longer survey.

B. Quality-Assurance Investment Survey Results

A summary of the results of the survey is presented below:

Question 1:[16] Does you firm's current definition of quality generally conform to the definition stated [below]?

> Quality can be defined in terms of performance levels, performance stability, reliability and longevity. One simple definition is conformance to specifications and/or fitness for use.

Finding: Four of the five firms--80 percent of the respondents--accepted, unmodified, the definition of quality as given above.

Companies were asked how their firm's definition of quality differed from the above traditional definition. The one differing firm responded that: "Our definition is broader and

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[16]The numbering of the questions refers to the number in the original questionnaire. See Appendix B.

includes the service and support behind our products contributing to total customer satisfaction."

Question 2: Companies were asked what percentage of their firm's total budget is allocated toward achieving quality. And what percentage of each budget subcategory is allocated toward achieving quality.

Finding: Regarding the percentage of total budget, four firms reported their average percentage over the 1980-1985 period, and all five firms reported this percentage for the current period (1988-1989). The average percentage of total budget allocated toward achieving quality over 1980-1985 was 12.8 percent and the average percentage in 1988-1989 was 17.5 percent (standard deviation of 10.5). Quality-related allocations increased 4.7 percentage points, or, stated alternatively, the average percentage of total budget allocated toward achieving quality increased 37 percent between these two time periods.

None of the firms reported the average percentage of sub-budget categories allocated toward quality for the 1980-1985 period, but several did for the 1988-1989 period. Four sub-budget categories were considered: operations, capital, R&D (if separate), and overhead. The average percentage of each of these sub-budgets allocated to achieving quality, with the number of responding firms in parentheses, is:

Budget Category[17]	Current Percent of Budget Category Allocated Toward Achieving Quality[18]
Operations	18.7 (4)[19]
Capital	27.0 (5)
R&D	26.7 (3)
Overhead	21.8 (4)

Comment: The above pattern of quality expenditures suggests that firms in the optical fiber industry are making significant efforts to build quality into all stages of their economic process, as opposed to testing for quality at the end of the production process. The largest budget percentages allocated toward quality are associated with capital and R&D. In fact, one respondent commented that in his company "Quality is emphasized through the team concept with customer representatives involved at all stages of production and planning, especially in R&D." Another respondent noted that "more emphasis is placed [today] on prevention versus inspection which in turn requires more training, and less product inspection. We have increased process audits at the same time as part of the thrust to prevent defects."

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[17] See Appendix F for a definition of each budget category.

[18] The budget allocations do not sum to 100 percent because they are averages across respondents.

[19] Number of respondents.

Based on discussions with several industry experts and several of the respondents (in a Delphi manner), a reasonable estimate of current total annual expenditures toward achieving quality by all firms in the industry is at least $25 million, and perhaps as high as $30 million. For an industry with current (1987 data) annual sales of $268 million, this investment corresponds to a quality expenditures-to-sales ratio of almost 10.

Question 3: Companies were asked to report the percentage of their firm's total budget allocated toward achieving quality is allocated to the following expenditures:

> Control includes operations such as materials inspection, in-process monitoring, completed-product inspection/testing and statistical quality control.
>
> Improvement involves procedural audits, analysis of process data, development of modifications to inspection procedures, process techniques, statistical quality control and quality awareness and training programs.
>
> Management defines and monitors a quality system, including management reporting, engineering-support functions and quality management (quality engineering and quality control).

Finding: All five firms responded to this question by noting whether the portion of their quality budget so allocated was significant (=2), minor (=1), or none (=0), as:

Functional Categories	Mean Response
Control	2.0
Improvement	1.4
Management	1.4

Comment: One respondent commented, when asked to compare quality expenditures in the above nontechnical areas to those in the technical areas (product and process technology), that in their company there was a trend during the last decade toward the nontechnical expenditures: "We are spending more time in training our management in areas necessary for quality improvement, and also analyzing our systems with regard to how they can be improved."

Question 4: Companies were asked to report the percentage of their firm's total budget allocated toward achieving quality that is allocated toward achieving certain objectives.

Finding: None of the firms reported the percentage of their quality budget toward achieving the following functional objectives for the 1980-1985 period. In all but one case, four firms responded for the 1988-1989 period as:

Objective	Percentage of Quality Budget[20]
Improving Product Performance	28.3
Reducing Attribute Variability	15.0
Increasing Product Reliability	16.5
Decreasing Need for Serviceability	5.0
Increasing Product Life	5.3
Improving Manufacturability (Includes improved materials and processes)	31.0
Other (Education/Training)	3.8

Comment: The majority of quality expenditures is allocated toward improving product performance and manufacturability. In fact, a spokesperson for one firm noted that the percentage of their quality budget allocated toward manufacturability had increased from 10 percent in the early-1980s to 50 percent today. However, in a statistical sense, there is no correlation between the percentage of quality expenditures allocated toward either improving product performance or manufacturability and either the percentage of the operations or capital budget allocated toward achieving quality (Question 2).

Question 7: Companies were asked to report the percentage of their firm's current total budget allocated toward achieving quality that is devoted toward measurement expenditures.

Measurement expenditures are those that yield information on certain attributes such as attenuation, dispersion, energy, area and frequency via direct, indirect, comparisons and interpolation/extrapolation approaches.

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[20]The budget allocations do not sum to 100 percent because they are averages across respondents.

Finding: The mean response from all five firms was 27.5 percent.

Comment: Based on an average of 17.5 percent of total budget being allocated toward quality and an average percentage of 27.5 percent of the quality budget being devoted toward measurement, approximately 5 percent of the total budget of firms in the optical fiber industry is devoted toward measurement expenditures. Using the estimate that total industry expenditures toward achieving quality are between $25 and $30 million, and 27.5 percent of total expenditures toward quality is devoted to measurement, then a reasonable estimate is that between $6.9 and $8.3 million is devoted toward measurement expenditures.

C. Evaluation of Quality-Assurance Investment Survey Results

The production capacity of the U.S. optical fiber industry increased over 50 percent from 1984 to 1985, and over 100 percent from 1985 to 1986. Industry experts report that capacity increased only about 25 percent from 1986 to 1990. The capacity utilization rate was only 59 percent in 1986, but has risen each year since then. Between 1980-1985 and 1988-1989, the average share of total budget allocated toward achieving quality increased from 12.8 to 17.5 percent.

These differing patterns of growth reflect the fact that the mix of activities changes over the life cycle of the production process. During the early-1980s, this industry was experiencing growth and was evolving toward a dominant product design, without a single set of industry-wide standards or performance criteria. With the measurement standards adopted in the mid-1980s, firms are now in a position to introduce specialized capital equipment and to emphasize process design to a greater degree.

Current[21] production capacity data and current market share data for each firm were correlated with the firm-specific responses to the questions above. In general, there was no significant correlation pattern. Larger firms or firms with a greater market share did not systematically allocate larger or smaller portions of their budgets toward achieving quality. Investment in quality is an industry-wide competitive strategy.

The only significant correlation (positive) between both size and market share is with the functional objectives of increasing product reliability and decreasing need for serviceability. A conservative interpretation of this finding is

[21]The most recent published data are presented in Appendix A. Those data were updated through discussions with firm representatives but to ensure confidentiality they are not reported here.

that a firm must achieve some necessary economies of scale before it can effectively compete in these two dimensions.

D. The Utilization of NIST as a Source of Quality-Related Information

NIST has a mission to conduct research related to aspects of quality, and to measurement in particular, and to transfer that knowledge to the private sector. All five of the U.S. firms in the optical fiber industry were asked about NIST as a source of information on quality.

Question 8: Companies were asked whether during the past three years their company obtained quality-related information from the National Institute of Standards and Technology (NIST).

Finding: Three of the five firms responded yes.

Comment: There is no statistical relationship between firms that utilize NIST information and either their size (production capacity) or their market share.

Of the three firms that have had contact with NIST, each was asked in the second part of Question 8 to rate this information on a five-point scale between 5=Very Important and 1=Not Important. The mean response from the three firms that have

obtained quality-related information from NIST was 4.3. Perhaps more important than the relatively high mean response is the fact that the range of responses was 3 to 5. No firm was unsatisfied with the quality information they received from NIST.

As before, there is no statistical relationship between a firm's response as to the relative importance of NIST information and either its size or market share.

One firm's representative reported that the quality of the information they obtained from NIST has improved over previous years, especially in the area of measurement research.

E. Assessment of Quality as a Strategic Tool

Given that AT&T, Corning and Alcatel account for over 90 percent of the U.S. market for fiber (sales as well as production capacity), their responses to the survey, summarized below, are a reasonable barometer of the use of quality as a strategic tool in the overall industry.

Question 5 on the survey relates to quality as a strategic tool. Responses to this question are important for verifying, along with other information collected in the survey, the

hypotheses that quality investments are becoming more pervasive throughout the production process.

The companies were asked to respond to nine strategy-related statements using one of four response categories: strongly agree (=3), somewhat agree (=2), somewhat disagree (=1), and strongly disagree (=0). We do not report the mean responses from the three firms below for reasons of confidentiality. In some instances, all three companies responded in the strongly agree category. Reporting a mean of 3.0 would reveal each company's individual response. Therefore, an alternative summary scale was devised to represent industry-wide opinion:

- If the mean response of the three companies is greater than or equal to 2.5, then the industry response is strongly agree.
- If the mean response of the three companies is less than 2.5 but greater than or equal to 1.5, then the industry response is somewhat agree.
- If the mean response of the three companies is less than 1.5 but greater than or equal to 0.5, then the industry response is somewhat disagree.
- If the mean response of the three companies is less than 0.5, then the industry response is strongly disagree.

<u>Statement 1:</u> Quality is increasingly achieved through product design rather than new production technology.

Industry Response: Somewhat agree.

Comment: These firms reported that while product design is increasing in importance relative to new production technology, both are important dimensions for achieving quality.

Statement 2: With respect to production, quality is increasingly achieved through distinctly new technology rather than modifying existing technology, for (1) mature products; (2) new products.

Industry Response: Somewhat disagree for both mature and new products.

Comment: It is our understanding of this industry that new technologies are being introduced at an increasing rate. With respect to technology, this is by no means a mature industry. Still, companies have not abandoned the use of technology modification as an additional way to achieve quality.

Statement 3: An important component of quality improvement is user feedback provided by marketing/sales personnel.

Industry Response: Strongly agree.

Comment: One company appended this statement by emphasizing the direct role of customer input into the research and design stages.

Statement 4: R&D provides important technical support to nontechnology, quality-related activities.

Industry Response: Somewhat agree.

Statement 5: Quality activities are guided primarily by what competing firms are doing with their product/process strategies.

Industry Response: Somewhat agree.

Comment: There was some disagreement to this statement because, as a respondent stated, "quality is now part of our corporate culture."

Statement 6: Improving product and process quality is a strategic option for GAINING market share.

Industry Response: Strongly agree.

Comment: It is our opinion from discussions with representatives from these three companies that they fully understand the global nature of the optical fiber industry and the competitive

pressures from foreign companies. There is no significant correlation between the companies' responses to this question and their share of the U.S. market.

Statement 7: Quality is an essential element of our cost-reduction strategies.

Industry Response: Strongly agree.

Statement 8: Service quality is now the key way for a vendor to be differentiated from other vendors (service quality includes time to delivery, technical support, etc.)

Industry Response: Somewhat agree.

Statement 9: On average, U.S. firms (other than yours) are willing to sacrifice some quality in order to introduce a product earlier than are Japanese firms.

Industry Response: Somewhat disagree.

In general, these responses suggest that the optical fiber industry perceives quality as an important element of their strategy for competing in the world market. There is evidence, too, that aspects of quality assurance are being introduced into the various stages of production, such as R&D, and that this is occurring through design as well as through new technology.

Qualitative impressions gathered through the interview process suggest that these companies would be in less agreement to these statements (and in more agreement with Statement 9) a few years ago than they are today.

Chapter 4: Comparing American Approaches to Quality Assurance to Approaches in Other Countries

A. Overview of Data Collection

The population of international producers of optic‼alfibe◂ was determined from the list of producers in Appendix A, in Table A.4 and from the Kessler Marketing Intelligence Fiberoptic Supplier Directory, 1988-1989. Each company was sent a short survey along with a cover letter explaining the purpose of this study. Seven responses were initially received.[22] A second mailing and follow-up telephone calls were made to several of the nonresponding firms for which we were able to identify the quality manager. These names came from our conversations with the American respondents. Unfortunately, this second-round effort produced no additional responses.

With limited information as to the production or production capacity of the international producers of optical fiber, we are unable to determine precisely how representative this sample of firms is. We have no reason to believe (based on our expost discussions with industry representatives) that the average

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[22]We learned from this exercise that the available sources of information to identify international producers of optical fiber are somewhat inaccurate. Some designated fiber producers are, in fact, only cable producers.

responses from these companies is not a reasonable approximation of "the rest of the world's" investment activity in quality. Nevertheless, care should still be exercised in interpreting these findings.

Information on the same six items relating to investments in quality assurance was requested from the international firms as was obtained from the U.S. producers.

B. Quality-Assurance Investment Survey Results and Evaluation

A summary of the responses from the international producers is presented below. Company names are not reported to insure response confidentiality. The six countries represented in this sample are Japan, Sweden, Italy, England, Yugoslavia, and Brazil.

Question 1:[23] Companies were asked to indicate whether or not their firm's current definition of quality conforms to the following traditional definition:

> Quality can be defined in terms of performance levels, performance stability, reliability and longevity. One simple definition is conformance to specifications and/or fitness for use.

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[23] The numbering of the questions refers to the number in the original questionnaire. See Appendix B.

Finding: Five of the seven firms accepted, unmodified, the definition of quality as given above.

Companies were asked how their firm's definition of quality differed from the above traditional definition. One firm responded that: "It concerns all production steps, from Planning and Design until Final Control of our products--not only 'conformance to specs'." The other firms responded that: [Quality is] "conformance to customer requirements."

Question 2: Companies were asked what percentage of their firm's total budget is allocated toward achieving quality. And what percentage of each budget subcategory is allocated toward achieving quality.

Finding: Regarding the percentage of total budget, four firms reported their average percentage over the 1980-1985 period. The average percentage of total budget allocated toward achieving quality over 1980-1985 was 6.6 percent (compared to 12.8 percent for the U.S. firms). Five firms reported an average of 12.2 percent of their total budget currently being allocated toward quality (compared to 17.5 percent for the U.S. firms).

None of the firms reported the average percentage of sub-budget categories allocated toward quality for the 1980-1985 period. This was also the case with the U.S. respondents.

Several firms did report this information for the 1988-1989 period. Four sub-budget categories were considered: operations, capital, R&D (if separate), and overhead. The average percentage of each of these sub-budgets allocated to achieving quality, with the number of responding firms in parentheses, is reported below along with the U.S. responses for comparison purposes:

Budget Category	Avg. Int'l Percentage	Avg. U.S. Percentage[24]
Operations	4.3 (5)	18.7 (4)
Capital	6.4 (4)	27.0 (5)
R&D	8.8 (4)	26.7 (3)
Overhead	5.2 (5)	21.8 (4)

Comment: In every instance the U.S. firms allocated, on average, a greater percentage of budget toward achieving quality. Also noteworthy is the similar relative allocation pattern between the international firms and the U.S. firms. Relatively greater percentages of capital and R&D budgets are allocated toward quality than of the operations and overhead budgets. This pattern is not inconsistent with the observation of quality assurance being built into the production process.

Question 3: Companies were asked to report the percentage of their firm's total budget allocated toward achieving quality is allocated to the following nontechnology-related expenditures:

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[24]The budget allocations do not sum to 100 percent because they are averages across respondents.

Control includes operations such as materials inspection, in-process monitoring, completed-product inspection/testing and statistical quality control.

Improvement involves procedural audits, analysis of process data, development of modifications to inspection procedures, process techniques, statistical quality control and quality awareness and training programs.

Management defines and monitors a quality system, including management reporting, engineering-support functions and quality management (quality engineering and quality control).

Finding: Five firms responded to this question by noting if the portion of their quality budget so allocated was significant (=2), minor (=1), or none (=0). These responses, along with those from the five U.S. firms, are:

Functional Categories	Int'l Mean Response	U.S. Mean Response
Control	2.0	2.0
Improvement	2.0	1.4
Management	1.4	1.4

Comment: The smallest quality allocation comes from the management budget. All 10 respondents (five U.S. and five international) reported that a "significant" portion of their control budget is allocated toward achieving quality. This finding again strengthens our conclusion that producers of optical fiber are building quality into the production process.

Question 4: Companies were asked to report the percentage of their firm's total budget allocated toward achieving quality that is allocated toward achieving certain objectives.

Finding: None of the firms, as was the case with the U.S. firms, reported the percentage of their quality budget toward achieving the following functional objectives for the 1980-1985 period. All seven of the international firms responded for the 1988-1989 period as:

Objective	Int'l Percentage of Quality Budget	U.S. Percentage of Quality Budget[25]
Improving Product Performance	17.1	28.3
Reducing Attribute Variability	17.7	15.0
Increasing Product Reliability	15.9	16.5
Decreasing Need for Serviceability	10.6	5.0
Increasing Product Life	6.3	5.3
Improving Manufacturability (Includes improved materials and processes)	15.0	31.0
Other (Education/ Training)	5.4	3.8

[25]The budget allocations do not sum to 100 percent because they are averages across respondents.

Comment: The relative distribution of allocations is less skewed among the international producers than among the U.S. producers. The relative ranking is, however, similar. Such similarity is not unexpected given the global nature of the optical fiber market.

Question 7: Companies were asked to report the percentage of their firm's current total budget allocated toward achieving quality that is devoted toward measurement expenditures?

> Measurement expenditures are those that yield information on certain attributes such as attenuation, dispersion, energy, area and frequency via direct, indirect, comparisons and interpolation/extrapolation approaches.

Finding: The mean response from all seven firms was 19.4 percent, compared to 27.5 percent for the U.S. firms.

Comment: Based on an average of 12.2 percent of total budget being allocated toward quality, and an average percentage of 19.4 percent of the quality budget being devoted toward measurement, then approximately 2 percent of the total budget of international firms in the optical fiber industry is devoted toward measurement expenditures. The corresponding percentage for the U.S. firms is 5. There is not sufficient information for us to impute a dollar value to this international percentage.

This simple comparison paints a consistent picture. U.S. companies are investing a greater percentage of their budgets toward achieving quality in the production of optical fiber than are the international companies. This fact may, in part, account for why U.S. producers have a significantly larger share of the world market.

PART III

ANALYSIS OF INVESTMENTS IN QUALITY ASSURANCE AND MEASUREMENT TECHNOLOGY IN THE U.S. SEMICONDUCTOR INDUSTRY

Chapter 5: Overview

Data on quality-assurance activities in the U.S. semiconductor industry[26] were collected through survey instruments. First, we developed a detailed questionnaire that served as a template for structuring a series of telephone interviews with quality-control executives at seven major U.S. semiconductor firms.[27] Second, a shorter version of the same questionnaire was mailed to firms that were not selected to be interviewed; we received adequate data from four of these firms.[28] The results reported in Chapter 6 reflect data collected from both the interviews and the questionnaire.

In the course of collecting these data, we found that responsibility for measurement activities within the companies we surveyed is separate from quality control. A separate

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[26]See Appendix C for a general description of the U.S. semiconductor industry.

[27]Larger semiconductor firms were selected because they met the criteria that the firm already have made significant investments in quality assurance.

[28]See Appendix D for a copy of the questionnaire form.

measurement survey was therefore designed and conducted.[29] Chapter 7 covers the results from the measurement survey.

Chapter 8 summarizes the findings and conclusions about investments in quality assurance and measurement technology in the U.S. semiconductor industry.

QFA's accumulated knowledge of operations and investment strategies in Japanese semiconductor firms allowed us to compare in more depth Japanese and American approaches to quality in the semiconductor industry. Chapter 9 focuses on how semiconductor firms in the two countries have integrated quality assurance into their overall business strategy and the different methods used to achieve their strategic objectives. Because Japanese firms are leaders in successfully incorporating quality into their overall corporate strategy, the information extracted from this discussion should provide a broader perspective for evaluating U.S. QA practices.

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[29]See Appendix E for a copy of the questionnaire form.

Chapter 6: Investments in Quality Assurance in the U.S. Semiconductor Industry

To place the 11 respondents to our survey of investments in quality assurance in perspective, there are an estimated 200 U.S.-based manufacturers of semiconductor devices. However, many of these firms are extremely small in size. The firms that responded to the QA survey represented over 50 percent, by value, of total integrated circuit (IC) production in the U.S. in 1989. Thus, our sample covers a large segment of U.S. semiconductor production, but it is biased toward larger firms. This was done by design, since it was believed that larger firms would be driving leading-edge QA practices.[30]

Our sample is also nonrandom in the sense that we believe we included all but two U.S. merchant semiconductor firms that are heavily investing in QA and would be considered leading-edge QA practitioners. For this reason, the averages derived from the sample likely overstate somewhat the average levels of investment for the entire U.S. semiconductor industry.[31] The results,

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[30]We use the expression "leading-edge" quality-assurance firms to denote those firms that have been the most aggressive in pursuing a competitive strategy based on quality improvements.

[31]Given the high level of competition in the semiconductor industry, the degree of overstatement is limited. Companies that do not meet minimum quality standards quickly lose market share--and minimum standards continue to become tighter.

however, are clearly indicative of the directions of change taken by a very large segment of the industry.

A. Quality-Assurance Investment Survey Results

The quality-assurance investment survey for the semiconductor industry collected data on each of the following seven issues:

(1) the definition of quality used by the U.S. semiconductor industry and how it has changed;

(2) trends in quality-related outlays as a percentage of total outlays by the firms;

(3) the estimated distribution of outlays for total quality by functional categories;

(4) the estimated distribution of outlays for total quality by strategic management objective;

(5) an assessment of quality as a strategic tool;

(6) identification of barriers to quality improvement; and

(7) measurement-related expenditures for quality assurance as a percentage of total outlays allocated toward measurement.

A summary of the responses for each item is presented below:

(1) The Definition of Quality Used by the U.S. Semiconductor Industry and How it has Changed

Question 1A:[32] Companies were asked to indicate whether or not their firm's current definition of quality conforms to the following traditional definition:

> Quality can be defined in terms of performance levels, performance stability, reliability, and longevity. One simple definition is conformance to specifications and/or fitness for use.

Finding: Only two firms accepted, unmodified, the definition of quality as given above. As shown below, many of these comments focused more on the process of QA, the related strategy of implementation, as opposed to differing in a major way from the basic definition.

Question 1B: Companies were asked how their firm's definition of quality differed from the traditional definition.

Finding: The definition of quality currently in use in the U.S. semiconductor industry is broader and more dynamic than the textbook definition used in our surveys and interviews. Firms

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[32]The numbering of the questions refers to the number in the original questionnaire. See Appendix D for a copy of the questions and Appendix F for associated definitions used with the survey.

are using a comprehensive view of quality. An extreme case is illustrated with the following quote from one company: "Quality is...an integral part of virtually everyone's performance criteria." The concepts of continuous improvement and prevention applied throughout the organization are central to definition of quality as practiced by today's semiconductor firms. The following quotations illustrate the view of the definition of quality as it is currently applied within semiconductor firms.

- "There is a broader definition applied [at our firm]: progression of quality to where the customer wants and desires are; we use statistical methods to drive to that new level. Ten years ago expectations were that you couldn't get to a level of below one percent or 0.65 percent AQL nor achieve defect per million below 200...What is required is what the customer wants, but the customer cannot always know--you constantly have to improve and get closer to the customer to meet his requirements...In the past, we relied upon inspection as the means of maintaining quality going out the door. Now [we are] into the appraisal era going into the prevention era."

- "The focus is on continuous improvement. Progress cannot be bounded...The given is meeting needs of the customer specifications. Objective is a continuous improvement in service levels, delivery, product value-added, production capability. This philosophy has been developed over the last four to five years...Customer expectations are also very important. [We] must conform to specifications, but expectations include more than just specifications."

- "The only way to get quality is through prevention--that is, the biggest change that has happened in our philosophy--we must adopt a more cost-effective approach to achieving quality...In the 1960s and 1970s, we were heavy on inspection and verification; then we adopted SPC techniques in the 1980s..."

- "A shift in [our] definition of quality initially took place in 1980-1981. [We] used to look at quality in terms of PPM [parts per million] product defects. However, [our] definition of quality has radically evolved into one of total quality performance and customer defined quality (which includes every part of the interface...). Things such as the following are included in the concept of quality: management decisions, customer interface, vendor interface, and total quality control. Quality is not a segmented function for most employees, but an integral part of virtually everyone's performance criteria."

Question 1C: Companies were asked whether their definition of quality changed within the past 10 years?

Finding: The definition of quality applied by the firms we interviewed has evolved significantly over the past decade. The changes can best be summarized by grouping QA practices into four successive stages described as follows:

> Stage 1: Inspection and Verification. This approach was influenced by the Department of Defense procurement philosophy of inspections; firms relying upon this approach would "inspect everything." In order to verify the life cycle reliability, stress tests and sometimes destructive testing were the means used to verify conformance to military specifications (Mil-Specs). This philosophy toward quality assurance permeated the U.S. semiconductor industry in the 1960s when the U.S. military market was the single largest market in the world for ICs.[33] Up through the

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[33]In 1960, consumption by the military represented nearly half the value of total U.S. consumption; by 1968, it was still over one-third. Only by the early-1970s did the military market decline to a fairly small portion of overall total U.S. semiconductor consumption, ranging between 5 and 10 percent of the total value of the U.S. semiconductor market. (Source for 1960 and 1968 market estimates: Robert W. Wilson, P. Ashton, T.

early-1980s, most U.S. semiconductor firms relied principally on inspection and verification methods to insure quality.

Stage 2: Appraisal. The next stage up from the heavy inspection philosophy toward quality assurance is appraisal. This puts emphasis on measurement, evaluation, and auditing of final product quality as well as insuring that purchased components and materials conformed with quality standards and performance requirements.

Stage 3: Prevention. Prevention is considered to be a more robust approach to quality assurance than either inspection or appraisal. It involves major changes in management philosophy such as designing quality into the product, application of statistical process control (SPC) techniques to manufacturing operations, and shifting the responsibilities for quality assurance into the operating organizations. Conventional quality-assurance organizations decrease in size and importance in firms applying this approach to quality assurance.

Stage 4: Total Quality Management (TQM) or Control.[34] This approach to quality assurance seeks to completely emulate the Japanese management philosophy on quality assurance. It incorporates all the elements of prevention, but goes on to a broader concept. Quality assurance becomes the responsibility of all levels of management and employees, while relationships with vendors and customers are aligned to reflect and support the total quality philosophy.[35]

Egan, Innovation, Competition, and Government Policy in the Semiconductor Industry (Lexington Books, Lexington, MA), 1980; p. 19.)

[34]The total quality management concept is discussed further in Chapter 9, which compares U.S. and Japanese QA practices.

[35]Texas Instruments, which states that it has a total quality control process in place, notes the following regarding TQM [quoting Kevin McGarity, Vice President of Semiconductor Marketing and Sales at TI]: "It [the emphasis on quality] has intensified, if anything. We might have all been nudged by the HP report, but now we are looking for what we here call TQC--total quality control. Part of that new phase in quality awareness is built on new computer-assisted manufacturing techniques using SPC and new sales campaigns emphasizing 'cost of ownership' as part of the buying price of electronic components."

Among the firms we interviewed, almost all the firms reported that they are currently in the prevention stage, or beyond it to applying some form of a TQM approach.

(2) <u>Trends in Quality-Related Outlays as a Percentage of Total Outlays by the Firms</u>

<u>Question 2A:</u> Companies were asked what percentage of their firm's total budget is allocated toward achieving quality.

<u>Finding:</u>

	Average During 1980-85[36]	Current
Percentage of Total Budget Allocated Toward Achieving Quality	10-20%	20-35%

<u>Comment:</u> For the most part, the responses were the qualitative assessments of senior QA managers who knew the orders of magnitude of quality expenditures and investments relative to the firms' total budget. No firm kept actual accounting records in categories that allowed a rigorous, documented break-out. Nevertheless, there was a relatively narrow range of responses, with one exception. One respondent reported that quality outlays

[36]Range reported reflects lower and upper bound of responses received. See comment for discussion of one exception.

were 5 percent today, compared to over 10 percent 10 years ago. This response, however, only related to items considered direct outlays for QA--inspectors, etc.--and these functions were being integrated into design and manufacturing and actually diminished in size through prevention programs.

Question 2B: Companies were asked what percentage of each budget subcategory is allocated toward achieving quality.

Finding:

Percentage of Budget Category Allocated Toward Achieving Quality[37]

Budget Category[38]	Average During 1980-85	Current
	(Percent)	
Operations Budget	25-70	10-25
Capital Investment Budget	0-10	10-60
R&D Budget	0- 5	5-40
Overhead Budget	20-50	5-15

Comment: The wide ranges of the estimates for the four categories reflects different corporate strategies as well as the fact that no firm keeps records on quality investments by these particular definitions of budget categories. Thus, the estimates

[37]Range reported for each category reflects lower and upper bound of responses received.

[38]See Appendix F for a definition of each budget category.

were made on the basis of expert judgment. Even with the wide variation in the estimates, several points emerge. First, as quality-assurance practices have shifted toward prevention and TQM in recent years, there has been a decline in the portion of the operations budget that is devoted to quality. Likewise, the portion of overhead outlays that were quality-related have dropped as firms have decentralized the quality function and applied quality-control practices that diffuse quality-assurance responsibilities throughout the organization. At the same time, the sharp growth in the share of the R&D and capital investments outlays that are quality-related reflects emphasis on reducing variation in product attributes and increased emphasis on design for manufacturability.[39]

Question 2C: Companies were asked to report whether their firms had shifted dollar expenditures related to quality in the past decade, from overhead for inspection and detection, toward spending more dollars on prevention in operations, R&D, and capital budgets.

Finding: All companies interviewed concurred that this shift has taken place over the past decade.

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[39] It is important to recognize that expenditures related to manufacturability and new product design are included in the R&D budget, not the operations budget.

(3) Estimated Distribution of Outlays for Total Quality by Functional Categories

Question 3A: Companies were asked what percentage of their firm's total expenditures to achieve quality is allocated to each of the primary areas of cost breakdown.

Distribution of Total Quality Expenditures[40]

Functional Expenditure Category[41]	Average During 1980-85	Current
	(Percent)	
Prevention	10-15	30-50
Appraisal	30-50	15-30
Internal Failure	20-40	20-20+
External Failure	15-20	10-15
Total	100%	100%

Question 3B: Companies were asked whether the proportion of quality-related expenditures in the following nontechnical areas has been growing.

- Control includes operations such as incoming-materials inspection, in-process monitoring, completed-product inspection/testing and statistical quality control.

- Improvement procedural audits, analysis of process data; development of modifications to inspection procedures, process techniques, statistical quality control and quality awareness and training programs.

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[40]Range reported for each category reflects lower and upper bound of responses received.

[41]See Appendix F for definitions of expenditure categories.

- Management defines and monitors a quality system, including management reporting, engineering-support functions and quality management (quality engineering and quality control).

Finding: All respondents agreed that quality-related expenditures in the nontechnical areas has been growing.

(4) The Estimated Distribution of Outlays for Total Quality by Strategic Management Objective

Question 4: Companies were asked to report the percentage of their firm's total budget allocated toward achieving quality that is allocated toward achieving certain objectives.

Finding:

Reported Distribution of Quality-Related Outlays by Management Objective[42]

Management Objective	Average During 1980-85	Current
	(Percent)	
Improving Product Performance	40-50	25-40
Reducing Attribute Variability	10-20	20-30
Increasing Product Reliability	5-10	10-25
Reducing Cost of Test and QA	10-15	15-25
Improving Manufacturability (Includes improved materials and processes)	15-50	5-15
Other (Education/Training)	N/R	5-20
Total	100%	100%

[42]Range reported for each category reflects lower and upper bound of responses received.

(5) <u>An Assessment of Quality As A Strategic Tool</u>

Question 5: Companies were asked to indicate their degree of agreement or disagreement with a series of statements regarding the role of quality as a competitive tool in the semiconductor industry.

Finding: The following summarizes the responses to each statement.

Statement	Consensus of Respondent Views
Quality is achieved through product design rather than new production technology.	Generally agreed with the statement.
With respect to production, quality is increasingly achieved through distinctly new technology rather than modifying existing technology.	
For mature products.	Generally disagreed with the statement.
For new products.	No consensus--some strongly disagreed, others tended to agree.
An important component of quality improvement is user feedback provided by marketing/sales personnel.	Most strongly agreed with this view.
R&D provides important technical support to nontechnology, quality-related activities.	Divergence of views--some strongly agree, some disagree.

Quality activities are guided primarily by what competing firms are doing with their product/process strategies.	Views range from mild agreement to strong disagreement.
Improving product and process quality is a strategic option for gaining market share.	Strong agreement.
Quality is an essential element of our cost-reduction strategy.	Strong agreement.
Service quality is now the key way for a vendor to be differentiated from other vendors (service quality includes time to delivery, technical support, etc.)	Most respondents strongly Agree--one firm strongly disagreed.
On average, U.S. firms (other than yours) are willing to sacrifice some quality in order to introduce a product earlier than are Japanese firms.	Range of views from strong agreement to strong disagreement.

(6) Identification of Barriers to Quality Improvement

Question 6: Companies were asked what single factor is currently the greatest barrier to improving quality in semiconductors.

Finding: Several respondents cited the continuing tension in new product development between the objectives of improved quality and reducing "time to market," (the time from product inception to consumer marketing). Other comments were more on behavioral issues:

- "Getting everyone [in the company] to understand that improvement is continuous and define what that takes. Don't stop at a fixed goal."

- "[The greatest barrier is] getting people to accept the broad definition of quality. The corporate culture keeps trying to narrow the definition of quality--but we'll be out of business if we don't make the change."

- "Mindset--it's changing in a lot of companies--getting top management and, more difficult, at the middle management level to change. [It's a] question of what the mid-level guys are being rated on, their performance ratings; certainly not everyone in the company is being graded on quality...Managers know the performance items, if quality is not on the list it would take a back seat..."

(7) <u>Measurement-Related Expenditures for Quality Assurance as a Percentage of Total Outlays Allocated Toward Measurement</u>

<u>Question 7:</u> Companies were asked to report the percentage of their firm's current total budget allocated toward achieving quality that is devoted toward measurement?

<u>Finding:</u> Responses ranged between 15 and 40 percent.

<u>Comment:</u> Given that the responding firms indicated that currently between 20 and 35 percent of their total budget is allocated toward achieving quality, this suggests that between 3 and 14 percent of the total outlays of the semiconductor industry is allocated toward measurement technology. In terms of 1988 budget outlays for the industry, this would suggest that between $560 million and $2.6 billion is invested annually by the

semiconductor industry in measurement technologies that support quality. Chapter 7 explores measurement-related investment in more detail.

B. Evaluation of Quality-Assurance Investment Survey Results

Over the past 10 years, the percentage of the responding firms' total budget for quality-related activity has roughly doubled. During this same period, the total size of the U.S. semiconductor industry also more than doubled, suggesting that total quality-related outlays in absolute terms increased four-fold over the past decade--an annual rate of increase averaging 15 percent. As quality-related outlays have grown rapidly, the survey results indicate that there has been a major shift in the quality-assurance practices of the U.S. semiconductor firms.[43] There is a consensus among the industry executives we interviewed that the following changes in U.S. quality-assurance practices has occurred:

- First, there has been shift toward spending relatively more dollars on prevention in operations, R&D, and capital budgets relative to spending on inspection and detection. Survey respondents estimated that the share of total

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[43]See Chapter 9, which compares Japanese and American approaches to quality in the semiconductor industry for further discussion of this issue.

quality-related expenditures being invested in prevention had more than doubled from the early-1980s to 1988. At the same time outlays for prevention sharply rose, outlays related to appraisal and internal and external failures declined--perhaps being cut nearly in half.

- Second, the nature of quality- and prevention-related expenditures shifted in favor of nontechnology expenditures, including control (including SPC), improvement (including training programs), and management (quality engineering and quality control practice).

- Third, in conjunction with the first two changes, U.S. firms adopted a definition of quality (or more correctly, a philosophy for quality) that goes beyond the notion that quality means only conformance to specifications and fitness for use. The most aggressive definition of quality we encountered among the firms we interviewed was that quality is "integrally involved with every aspect of operations... One hundred percent of all resources are dedicated to quality..."

- And, fourth, the relative importance of various objectives to be achieved through quality outlays has changed from improving product performance and manufacturability to reducing variability of the product attributes, increasing product reliability, and reducing the cost of test and QA. This shift is the operational outcome of the broader trend favoring nontechnology expenditures as the means to achieve quality improvement.

The following points emerged from the interviews with regard to the strategic objectives that U.S. firms are trying to achieve by increasing and reallocating their quality-related outlays.

- In the future, competitive advantage in the manufacturing arena will come less from distinctly new technology; more market share leverage will be gained from improving and refining existing technology.

- Closer organizational coupling between device-makers and device users is seen as important to improving quality, and,

at the same time, service quality is seen as growing in importance as the means to differentiate the firm's product in the marketplace.

- Quality is considered an essential tool for driving cost reduction.

- There is a mixed assessment of the role of R&D in the process of supporting improvements in quality assurance. Responding firms generally indicated that the share of the R&D budget devoted to quality activities had grown significantly (supporting increased manufacturability and new product designs and improvements). However, there is no strong support for the proposition that R&D significantly supported nontechnology activities for quality assurance (incoming inspection, audits, applying SPC, training, and a quality management reporting system).

The quality-assurance investment survey results indicate that there has been a substantial change in quality-assurance philosophy in the U.S. semiconductor industry over the past decade. Reflecting that change in philosophy, there has been a major increase in the overall size of QA investments as well as a major redistribution of where U.S. semiconductor firms are investing to support QA. Measurement-related investment has been one area where the industry sustains a high and growing level of investment in support of meeting its quality objectives. The next chapter focuses specifically on measurement-related investments by the semiconductor firms and indicates where firms are making those investments as well as the relative degree of importance of NIST in supporting this area.

Chapter 7: Analysis of Investments in Quality Assurance in the U.S. Semiconductor Industry: Measurement-Related Investments

A. Measurement-Related Investment Survey Results

Four issues were covered by the questions in the separate measurement-related survey.[44] A total of nine firms responded with data on those measurement-related issues and the results are summarized below.

(1) Areas Where Measurement Technology is Important

Question: Companies were asked to rank, for the period before 1986 and the current period, the relative importance of the sources of measurement technology used to achieve quality.

Finding: There was no significant change in the relative rankings reported for the pre-1986 period versus the current period. The responses indicated the following order of importance for the sources of measurement technology:

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[44] See Appendix E for the survey of measurement technology investment.

Relative Importance of Different Sources of Measurement Technology

Most Important:[45]	Internal R&D Division NIST Operating Divisions Standards Bodies (ANSI, ASTM, etc.) Trade Associations
Middle:	Federal Laboratories (other than NIST) Suppliers Universities
Least Important:	Customers SRC SEMATECH

(2) Role of NIST in Supplying Measurement Information

Question: Companies were asked whether during the past three years their company obtained quality-related information from NIST?

Finding: All respondents stated YES.

(3) Degree of Importance of NIST Information

Question: Companies were asked to rate the degree of relative importance of the information received from NIST.

[45] Respondents were asked to provide a ranking of the relative importance of 11 organizations that are sources of measurement technology. Based on the average of the rankings supplied by respondents, these 11 organizations were clustered into the three tiers of most important, middle, least important sources.

Finding: Responding firms rated the importance of the NIST information to be 4.1 on a scale running from one (not important) to 5 (very important).

Comments received from respondents on the role of measurement technology and NIST's relationship to the industry include:

- [The NIST information we receive] pertains to standard reference materials and step height measurements in optical and SEM systems.

- Research cycle time has been the key issue limiting the usefulness of the NIST contribution. We could sacrifice some depth for speed.

- Mature products need little attention with exception of process monitors, whereas new products are measurement-intensive.

- Joint projects with industry are essential, along with timely delivery of results. We must shorten the R&D cycle for SRMs and procedures by a factor of three. This can only be accomplished through adequate funding and, more importantly, a change in the NIST culture.

- If the U.S. is to be truly competitive in the semiconductor market, especially with Japan, NIST simply must be given funds and staffing to provide measurement standards in a timely manner; most important is a submicron CD measurement standard.

- NIST and traceable standards are what we use to measure equipment and product quality.

- The semiconductor industry faces tough competition from international suppliers, particularly the Japanese. For us in the U.S. semiconductor industry to remain viable, we need to convince users that we build as technically sophisticated and reliable products as our international competitors.

- The investment in measurement is increasing rapidly...[if one] includes items like new testers in the estimate [of measurement investments], it takes hours to test a part today with fault grading.

- Standards are critical for manufacturability in that they will decrease variability and increase control of tools... [See] the importance for measurement in the test/assembly/ fab stages rather than in the earlier stages such as product design.

- [For this company] NIST is not the primary supplier of metrology/standards information. [They] rely on information from industry associations, SRC, SEMATECH, federal labs, and other standards bodies before NIST. NIST is primarily relied upon for equipment measurement; SEMATECH for early-warning reliability, JEDEC for vehicle development, and other reliability symposia are also relied upon. NIST would be higher on the list, but its primary downfall is in communications. The other sources of standards/metrology information make their applications easier to absorb. They rely on individual participation from companies. Companies are able to influence, participate and directly communicate back with these other resources...NIST needs a lot of improvement in the areas of communications and technology transfer.

- NIST should take over the leadership on MIL STAN 45662; the military is very arbitrary and does not keep up with the technology very well; there is no exercising of the standard without good technical leadership.

(4) <u>Application of Measurement Technology</u>

<u>Question:</u> Companies were asked where in the semiconductor business measurement technology and expenditures are relatively more important in terms of their firm's overall competitive position.

Finding:

Relative Importance to Competitive Position

	New Product[46]	Mature Product
Most Important:	Wafer Fabrication R&D[47] Product Design	Wafer Fabrication Materials Procurement Assembly/Test
Middle:	Equipment Procurement Materials Procurement Consumables Procurement	Equipment Procurement Qualification as Vendor Consumables Procurement
Least Important:	Assembly Test Qualification of Vendor	Marketing of Final Product R&D Product Design

B. Evaluation of Measurement-Related Investment Survey Results

The results of the quality assurance and the measurement technology surveys confirmed that measurement technology plays an important role in supporting the competitive position of the semiconductor industry. Both for new and mature products, wafer

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[46]Categories of semiconductor business activity are listed in order of importance. Based on the average of the respondent rankings, these activities were clustered into the three tiers of most important, middle, least important.

[47]Includes new product development.

fabrication is the portion of the U.S. semiconductor business where measurement technology was judged to be most critical to the competitive position of the average firm.

The survey results also confirmed that the relative importance of measurement technology for quality-related strategies in the semiconductor business varies relative to whether a product is early in the product life cycle or in a mature stage. For mature products, measurement technologies have their greatest leverage in those areas of the semiconductor business that are under greatest competitive pressures from international competition--manufacturing operations and materials procurement. For new products, measurement technology has a major role in supporting R&D and product design as well as wafer fabrication.

The consensus of the respondents was that, in addition to the company's own internal operating division and R&D division, NIST, the standards bodies and trade associations were the most important sources of measurement technology. SEMATECH ranked among the least important, but this merits two comments. First, several of the respondents in their discussion of this question identified SEMATECH as among the more important institutions supporting measurement technology; and, second, the relative newness of SEMATECH as a support institution to the industry may

have influenced some respondents not to rank its role as very significant.

Lastly, when we focused only on NIST, all the surveyed firms indicated they had received NIST information and felt that it had been at least moderately important. However, it was clear to us that these results were heavily influenced by the fact that the respondents had worked closely with NIST on some project. These respondents uniformly gave NIST a very high rating.

One important item that emerged indirectly from the conduct of both the measurement and the quality-assurance surveys in the semiconductor industry was the need for NIST to improve its visibility with different levels of management. During our field work, we found that only a very limited number of semiconductor managers had a general feel, much less a specific understanding, of the type of activities that NIST has undertaken in support of the industry. Managers who had been directly involved with NIST programs were generally favorable--some extremely positive--about the role that NIST has played in supporting the industry. The large number of executives--even those with substantial experience in, and responsibility for QA activities in their companies--who simply were unaware of NIST's role and its activities vis-a-vis the industry would suggest that communication can and should be improved.

Some interviewees went beyond criticizing the general lack of communication. They noted that NIST programs, while excellent in content focus, were too slow to yield results or that the results were not transferred in a user friendly way to a broad audience in the industry. NIST may want to try to verify that these perceptions are indeed widely held.

Chapter 8: Summary of Results of the Two Surveys of Investments in Quality Assurance and Measurement Technology in the U.S. Semiconductor Industry

The results of the quality assurance and the measurement technology surveys indicate that all three of our initial hypotheses were affirmed. To summarize, for the U.S. semiconductor industry:

- Hypothesis 1: Quality has become an increasingly important "input" to the activities of U.S. firms over the past decade.

  Quality-related investments have grown relatively faster than the rate of growth of the industry overall and faster than investment in R&D or capital expenditures for equipment and structures.

- Hypothesis 2: Quality investments are becoming more pervasive.

  Our evidence supports the conclusion that quality has become a competitive tool that is more persuasively applied. Firms saw quality investments as important not only in terms of improvement of the end-product, but as a tool to reduce cost in manufacturing, a means to improve market share, and an aid to improve time to market. However, improved manufacturability was receiving less direct QA investments; firms were applying nontechnology-based management techniques to refine various aspects of manufacturing practices in order to reduce product variability and increase product reliability. Thus, the diffusion of quality-assurance investments spilled over beyond the traditional narrow confines of the manufacturing floor into marketing and R&D.

- Hypothesis 3: Measurement technology-related investments are a significant component of quality-related investments.

  The data from the survey indicates that measurement-related investments represented between 15 and 40 percent of total quality-assurance investment--a significant portion of overall total quality-related investments.

Chapter 9: Comparing Japanese and American Approaches to Quality Assurance in the Semiconductor Industry

A. Introduction

Japanese firms--including Japanese semiconductor producers--are widely viewed as being at the forefront in successfully incorporating quality into their overall corporate strategy. Comparing U.S. and Japanese management practices with respect to quality is, therefore, one useful way to gain additional perspectives on the changes in U.S. quality-assurance investments discussed in Chapters 6 and 7.

We developed three hypotheses for studying QA philosophy and practice in U.S. and Japanese semiconductor firms. First, that among leading-edge practitioners of quality-assurance strategies in both countries, the differences in design of the overall strategy are small. Second, firms in both countries define their quality strategies differently from the classic definition of quality that focuses only on "fitness for use" concepts. Third, where differences exist, they tend to exist in the techniques of implementation of the quality-assurance strategies.

Our evaluation of differences in Japanese and American approaches to quality in the semiconductor industry is not based

on a rigorous empirical comparison of quality levels. In the case of the semiconductor industry, there is no general empirical standard that all firms must strive to achieve for all products. As one Japanese semiconductor executive stated: "LSI [large-scale integration] quality varies according to the manufacturer and the type of LSI. LSI quality also differs according to the manufacturing plant, even in the case of the same manufacturer and type of LSI...Even LSI manufacturers determine LSI quality according to the users' requirements. In other words, LSI quality varies according to the manufacturer."[48] Our approach, therefore, will be more qualitative, focusing on how semiconductor firms in the two countries have integrated quality assurance into their overall business strategy and the different methods used to achieve their strategic objectives.

We start our analysis by identifying some of its limitations in Section B. Some of these limitations arise from the inherent difficulty of setting the boundaries for a topic as broad as quality. To explore fully differences between U.S. and Japanese management approaches in this area, we could have started at the broadest level--contrasting, for example, differences in engineering culture and then move toward more specific elements

[48] Nikkei Electronics, "User, Manufacturer Cooperation in Quality Assurance," June 1988.

where differences are present. However, we have taken a more limited approach and begin at the more specific level.[49]

Next, in Section C, we describe some general structural features of the semiconductor industry, including important aspects of the manufacturing technology, that influence quality-assurance practices. This is done to provide a general background for those readers who are not familiar with the industry and its technology. Also, in discussing the general structural features that are important to quality-assurance practices, we define a framework that will apply in subsequent sections of our analysis.

Section D addresses how Japanese corporate management integrates quality-related goals into its business strategies.[50] One point that will be explained in detail is that the major Japanese semiconductor firms have what we will define as a manufacturing-driven business strategy. While not every American

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[49]For a discussion of Japanese engineering culture and its impact on Japanese management practices observed in the semiconductor industry, see William Finan and Jeffrey Frey, The Effectiveness of the Japanese Research-Development-Commercialization Cycle: Engineering and Technology Transfer in Japan's Semiconductor Industry (Semiconductor Research Corporation, Research Triangle, NC), September 1989.

[50]We base our conclusions in this chapter on translations of Japanese presentations and articles related to quality, and interviews with Japanese and American engineers.

firm needs to emulate the Japanese strategy, some American semiconductor firms must build their strategic strengths around manufacturing excellence in order to effectively compete globally against their Japanese competitors.

Understanding the Japanese approach to quality allows us to make some comparisons with the U.S. approach in Section E. The U.S. evolution of the philosophy of quality has been heavily influenced by the Japanese. There are differences though in the implementation and integration of the philosophy within the organizations of the two countries. These differences are principally the result of different key end-markets and technology drivers.

Section F summarizes the U.S.-Japan comparison of quality-assurance strategies and offers several issues NIST should consider for further evaluation.

B. Aspects of Quality Management in Japan Not Addressed in This Study

Like many things in Japan, the Japanese initially relied upon quality-related management practices and techniques that were pioneered outside Japan. The Japanese semiconductor industry was just one of many Japanese industries that benefited

from the broad diffusion of quality-related ideas that were applied throughout Japanese industry beginning in the 1970s.[51]

After having assimilated Western quality practices, the Japanese gradually modified and extended them. With the roots of Japanese quality-related practices firmly tied to the West, it is not particularly interesting to draw comparisons between the U.S. and Japanese quality-related management practices over a long period of time. What becomes more interesting and relevant is to focus on how Japanese quality-related management practices evolved in the past two decades--especially since about 1980.[52]

A general set of quality-related management practices that are widely used in Japan, including the semiconductor firms. An example of this type of practice would be the use of Quality

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[51]One Japanese semiconductor R&D director has written regarding this period: "Quality control was the national priority and a matter of life or death for the Japanese." Kaneyuki Kurokawa, "Quality and Innovation," IEEE Circuits and Devices Magazine, July 1988, p. 3. For a brief summary on this point, also see The Economist, September 23, 1989, "How to Build Quality," p. 95.

[52]The reason for focusing on the period since 1980 is that concurrent with the evolution of quality management practices during this period was a major evolution in semiconductor technology. Specifically, semiconductor process technology entered a new era of especially demanding process requirements. For the sake of simplicity, this can be dated as beginning around 1980. We will have more to say on this point in Section C where semiconductor process technology and its interaction with quality management practices is presented.

Circles "...which organize workers to study and deal with productive problems on their own initiative..."[53] By one estimate there are over one million quality circles operating throughout Japanese industry.[54]

General support of the quality strategies of individual Japanese firms is the large number of associations that deal directly or indirectly with quality in the Japanese semiconductor industry. Of particular interest is how these organizations interact with semiconductor firms.[55] Several of these associations have played an important role in training Japanese managers in quality practices and instilling in Japanese industries the recognition that quality is an attribute that drives overall industrial competitiveness.[56] Among the more

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[53]See James C. Abegglen and George Stalk, Kaisha, The Japanese Corporation (Charles E. Tuttle, Tokyo), 1985, p. 182. For a Japanese explanation of how quality circles function, see Shoji Shiba, "Moving in the Right Circles," Look Japan, August 1989, pp. 28-29.

[54]See "Findings of the U.S. Department of Defense Technology Assessment Team on Japanese Manufacturing Technology" (Draft), November 1988, p. 39. The report goes on to state: "The success of Quality Circles is well known and well documented."

[55]For example, there is an organization designated the QC Circle Headquarters whose goal is to "promote the spread and development of QC circles nationwide." Look Japan, op. cit., p. 29.

[56]The Defense Technology Assessment Team noted: "...a national momentum for continuously higher quality seems to be well entrenched throughout the Japanese industrial base," op. cit., p. 38.

frequently cited examples would be the Japan Productivity Association[57] and the Japanese Union of Scientists and Engineers.[58] Also currently active in developing and applying common quality-related standards in the semiconductor industry are the Japan Reliability Center and indirectly, the laboratories and engineering groups of Nippon Telegraph and Telephone (NTT).

We should not leave the impression that these types of "background" activities that support quality enhancements are unique to Japan. Obviously, they also play a role in the U.S. context. For example, the Malcolm Baldrige National Quality Award has an impact on the U.S. semiconductor industry analogous

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[57]This organization's history illustrates very nicely the point regarding Japan's willingness to go outside for ideas and technology. The Japan Productivity Center (JPC) was set up in 1955 as the result of U.S. government initiatives to foster productivity improvements in Japanese industry. Since its inception, the organization has sent over 26,000 Japanese executives and workers abroad to visit and study; at the same time it invited over 700 foreign experts to Japan. "Although the knowledge acquired by these overseas study teams and trainees influenced all phases of the economy, the main contribution was in the introduction of modern management techniques...Thus, the Japanese economy underwent a 'quiet revolution' through which it acquired the strength and system with which to meet the challenges of the age of innovation." Source: "Productivity Movement in Japan," Japan Productivity Center, May 1986; p. 9.

[58]This organization has also been important in transferring Japanese ideas on quality outside Japan. According to one account, in the past 11 years, over 8,000 people came to the Japanese Union of Scientists and Engineers to learn about total quality management concepts. See S. Shiba, "Universal Quality," Look Japan, October 1989, p. 32-33. See Section D of this chapter for a discussion of the total quality concept.

to the impact that the Deming Award has had in Japan.[59] There are also a number of support-type organizations in the U.S. that are involved in the promotion of quality goals and the training of managers to give them the management tools to achieve the goals.[60] In Japan, there may be more of these organizations and, due to the nature of Japanese corporate culture, it may be easier to change corporate practices through the use of these support organizations.

We do not delve into comparing how these more general institutional forms differ between the U.S. and Japan. It is our assertion that Japanese semiconductor organizations have less difficulty integrating these broad societal goals into their particular management objectives.[61]

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[59]Based on interviews with U.S. semiconductor executives. Also Motorola Corp., which was among the first recipients of the award, has undertaken a major effort to push for other U.S. firms to compete for it. See "Moto Rewards Award Seekers," Electronic Buyers' News, September 25, 1989, p. 1.

[60]One difference, however, is that in the U.S. many of these quality training organizations are private consulting-type organizations as opposed to the industry association or volunteer association format in Japan. This alone might suggest that quality is not always free--at least not in the U.S.

[61]As mentioned in the introduction to this chapter, we would need to get into issues of differences in engineering culture to support this assertion. Such a discussion would take us well outside the focus we want to take in this paper. Factors that influence Japanese engineering culture include the Japanese engineering education system and the training and socialization that goes on in large Japanese businesses. See W. Finan and J. Frey, op. cit., pp. 16-48.

C. Structural Features of the Semiconductor Industry Important to Quality Strategies Observed in Japan and the U.S.

It is useful to identify structural features of the semiconductor industry that have had an influence on the quality strategies observed in Japan and the United States.[62] There are two structural features that are important to our analysis: the evolution of semiconductor technology--especially the role of "technology drivers;" and the external relationships of semiconductor manufacturers--i.e., the organization of end-markets and the role of semiconductor equipment and materials infrastructure in supporting quality assurance in semiconductor manufacturing.

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[62]Compared to Japan, the U.S. semiconductor industry has a far more complex structure in terms of the number and variety of organizational forms. So-called captive producers whose production is totally consumed by a parent systems organization plays a far more important role in the U.S. industry than in Japan's. Our discussion of market organization excludes covering this type of organization and instead focuses on the merchant producer whose production is totally or predominately sold into the open market. Captive semiconductor organizations face a different set of management objectives relative to merchant semiconductor organizations. Most of the data collected for this report related to the semiconductor industry were developed through questionnaire data provided by U.S. merchant semiconductor firms.

C.1 Evolution of Semiconductor Technology and Its Impact on Quality-Assurance Practices

The evolution of semiconductor technology over the past decade has significantly impacted the quality-assurance strategies applied in the semiconductor industry. As will be explained in Section D in detail, most of the major Japanese semiconductor firms have pursued a strategy based on manufacturing superiority. Critical to the success of their strategy was the need to maintain a leading-edge position in semiconductor memory technology. The role of semiconductor memory, and DRAMs especially, as the "technology driver" for very large-scale integrated circuits (VLSI)[63] is widely recognized. The first part of this section explains the concept of technology driver and how differences in technology drivers applied in Japan and the U.S. influenced the development of management strategies related to quality assurance.

Maintaining a leading-edge position in memory technology depends on being able to drive the leading-edge of process

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[63]One commonly used measure of circuit complexity is the "scale" of integration that measures the number of active circuit elements (sometimes simply a count of transistors in the device). Large-scale integration (LSI) is considered to be devices with between 1,000 and 100,000 active elements; very large-scale integration (VLSI) is considered to be devices with between 100,000 and one million active elements; and ultra large-scale integration (ULSI) is considered to be devices with more than one million active elements.

technology and then being able to successfully apply the new process technologies in high-volume manufacturing operations. In the second part of the section, we identify the elements of process technology that have impacted most significantly on the quality-assurance process.

The third part of this section looks at issues related to product design developments, especially in semiconductor logic technologies. These developments have posed new issues of product testing and reliability assurance for semiconductor producers. Because of these developments, the Japanese semiconductor managements have had to confront quality-assurance issues that are less strongly coupled to their areas of strength in high-volume process development and manufacturing.

"Technology Drivers" and Their Role in Influencing Quality-Assurance Strategies

The term "technology driver" refers to a semiconductor product family that has both sufficient market scale and continuing requirements for application of leading-edge technology that it significantly influences or "drives" the technology for other product lines. As such, for an individual semiconductor producer, this strategic technology-driving product impacts the firm's leading-edge engineering disciplines across

most of the principal phases of the product life cycle, i.e., product development, manufacturing, and supporting infrastructure. The technology-driving product implies a key market that provides a continuing focus for successive generations of products, and a requirement for moving this new technology into manufacturing practice at an early date. Further, volume demand for the initial products must be realized before the next technological cycle makes these products obsolete.

Management disciplines developed around supporting the technology-driver product are gradually applied across other segments of the semiconductor producer's organization. Important to this study is the fact that a technology driver tends to be the pacing product with respect to establishing quality-related management practices that are then applied across a wider spectrum of the firm's products and processes.

Semiconductor memories--especially DRAMs--have been the dominant technology driver, especially for the major Japanese semiconductor producers, over the past 15 years. It is important to note, however, that DRAMs principally drive process and manufacturing technology. Other aspects of semiconductor technology, design and test, for example, are not impacted by DRAMs to the same degree. Thus, there is a set of quality-

assurance issues related to nonmemory, logic products, that cannot be addressed by using DRAMs as technology drivers.

American semiconductor firms have used a number of alternative products to serve the role of technology driver in recent years. The greater diversity in technology drivers is partly a result of the major withdrawal of American firms from the strategic DRAM market, but it also reflects a greater diversity in processing requirements. Depending upon their particular technology requirements, American firms have used static RAMs and EPROMs,[64] and more recently, microprocessors, peripherals and even high-density semicustom products as high-volume drivers for their respective product segments. In doing so, they have drawn principally upon the base manufacturing technology and infrastructure support developed for DRAM front-ends--which means increasingly Japanese technology.[65]

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[64]See Appendix C for a definition of these semiconductor product categories.

[65]There are technology drivers for other categories of integrated circuits, but their focus and impact has been restricted to lower density levels; e.g., SSI/MSI or LSI. There are also technology drivers for the manufacturing processes for specialized products apart from high-volume products. These include low-volume high-density gate arrays, special analog circuits, gallium arsenide digital products, microwave, etc. Still, even these special products require accessing the base silicon manufacturing technology and coupling it to an appropriate requirement for their needs.

Evolution of Semiconductor Process Technology and its Impact on Quality-Assurance Practices

Table 9.1 indicates some of the major changes that occurred in semiconductor wafer processing characteristics since 1980. Since that time, the technology of wafer processing progressed from being able to support a scale of 100,000 elements per device to supporting a scale well over one million elements per device (ULSI).

Table 9.1

Trends in Wafer Fabrication Parameters

(1) Level of Integration	LSI	VLSI	ULSI
(2) Products (DRAM)	16K	256K-1M	4M
(3) Date of First Commercialization	1979	1982/ 1985	1989
(4) Thruput, Wafers/Month	10K	30K	50K
(5) Total Process Steps/Lot	100	230-400	550
(6) No. of Types of Equipment	40	100	120
(7) Total Equipment Count	70	300	400
(8) Database Records/Lot	100	5,000	10,000

Source: Toshiba

Simultaneous with the evolution of leading-edge product technology to the level of ULSI complexity, the scale of wafer processing facilities also increased. In the LSI era, for example, wafer fabrication plants considered to be high volume typically processed 10K wafers per month. This increased to 20K-30K wafers per month in the VLSI era. In the ULSI era, some

plants are targeted to produce 50K wafers per month (see Table 9.1, line 4).[66] Thus, just as the product processing requirements grew more complex, the manufacturing facilities were being scaled up to produce these more complex devices at significantly higher volumes.

Concurrent with these changes, the complexity of the processes being run to produce leading-edge memory devices also increased. Whereas the number of processing steps--that is, the discrete number of operations applied to each wafer in each lot over the course of fabrication--was roughly 100 for the LSI-scale device, this grew by almost six-fold by the ULSI era. (See line 5, Table 9.1.) The growing complexity of processing requirements is also reflected in the increased variety and total number of equipment types. By the ULSI era, the number of different types of equipment needed on the fabrication line will have tripled over the number needed to produce LSI scale devices--raising the total count of equipment on the line almost six-fold.

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[66]While some of these fabs have already been built, it is not likely that there will be many more. The economies of scale for those large plants are questionable. Producers have found that it is more advantageous to refine their manufacturing practices with plants scaled to the 20K-30K level of wafer starts per month.

The last line in Table 9.1 provides a useful way to summarize the implications of the changes in scale of processing combined with the increased complexity of the process being run; it shows the number of database records manufacturing engineers need in order to monitor process variables and correlate lot history and engineering test data. In the LSI era in order to monitor the process variables during wafer processing, roughly 100 database records would be required to track each lot or batch of wafers through the course of processing the wafers. This grew 50-fold in the VLSI era and today is expected to be 100-fold greater in the ULSI era. Thus, quality assurance in the ULSI era simply could not be accomplished with the same management methods that were viable for the LSI era of semiconductor technology.

Despite the trends defined in wafer fabrication parameters discussed above, the Japanese memory producers were able to continue to sustain quality performance, if measured strictly in terms of parts per million (PPM) defects. Japanese memory users report that after one to two quarters of adoption of a new generation of memory, failure rates would decline into the range of 100 to 200 PPM.[67]

[67] Nikkei Electronics, op. cit., Figure 3 and related discussion.

There was another aspect to evolution of device technology that added to the difficulty of simply extrapolating past quality-assurance practices forward to newer generations. This point is best understood by looking at a different dimension of the change in semiconductor technology--the increasing scale of the devices being produced. The increasing scale of device was the increased number of elements per device. Even as devices were being produced with more elements per unit area (or higher density), they were simultaneously being produced with smaller feature sizes.

Table 9.2 summarizes this evolution by indicating the minimum feature size for successive DRAM products and the area of the average die being produced at each level. To hold maximum yield constant across successive generations, there was a requirement in the manufacturing process for a reduction in the size of the average defect generating particle. The move to higher-density (or larger-scale) devices meant that the conditions under which wafer processing took place had to be kept under stricter control--the Japanese would like to say "defect free."

Table 9.2

Defects Per Finished Wafer

	64K	256K	1M	4M
Minimum Feature Size (microns)	3	2	1.2	0.8
Die Size (square cm)	0.18	0.3	0.5	0.9
Yield[68]	80%	80%	80%	80%
Defects/Square cm	1.4	0.83	0.5	0.28
Defect Size (microns)	0.3	0.26	<0.12	<0.08

Source: Oki Electric

The evolution in semiconductor technologies over the past decade summarized in Tables 9.1 and 9.2 put tremendous pressure on semiconductor managements to find new means to continuously improve their quality. All aspects of manufacturing were impacted, including production flow scheduling, lot tracking, in-process test data generation, equipment control and monitoring capability, facilities layout and construction techniques, fluids control (both air and water), and equipment maintenance practices.

These changes in turn impacted the way quality-assurance activities had to be organized and managed. For example, simply conducting final inspection of the product was not sufficient. The high volumes required in-process controls. In the past,

[68]In this case, the table indicates that given the die size and minimum feature size, in order to achieve an 80 percent yield, what level of defect density and maximum defect size must be attained in the manufacturing operation.

these controls were based on statistical process control (SPC) methods, but in the ULSI era, the Japanese have found that previously applied SPC methods are not adequate. As one Japanese executive said:

> "Moreover, when the 4-Megabit era arrives, the number of production processes will increase even more and process margins will decrease. It will probably be more and more difficult to pinpoint defective spots and causes of defects with characteristics values of completed devices. There is no other way than discovering abnormalities at producing phase of each process and eradicating poor conditions in order to maintain and improve yield. In facility maintenance, technology to discover abnormalities early is required of not only hardware problems but fluctuations and changes in product quality. So quality maintenance activities become important."[69]

Manufacturing plants operating at high levels of wafer starts also generate a special set of pressures on the manufacturing organization. It must be capable of rapidly driving yields up once a new product commences production in order to minimize scrap--which carries an enormous cost penalty at these high levels of wafer starts per month. And the organization must have the discipline to efficiently sustain high yields once they have been attained. As one Japanese semiconductor executive stated:

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[69] H. Horikuri, LSI Production Headquarters, NEC, "Current Status and Problems of Production System," paper presented at Super LSI Ultraclean Symposium No. 6, Tokyo, Japan, June 1988.

"Yield improvement, which is the great problem in the wafer process, is not merely mastering stable functions of facilities due to special features of the production process [i.e., decrease downtime]. In addition, ceaseless efforts are made to decrease fluctuations of managing parameters and to shift the center value of management into the direction in which yield will improve. In other words, improvement in capabilities of the process is continued endlessly."[70]

These pressures of dealing with more and more complex processes, yet still sustaining high yields in production affected the way both U.S. and Japanese managements dealt with the problems of quality assurance. Over time a more robust, more complex approach to quality assurance was required to keep pace with evolution of the technology.

Developments in Logic Device Technology That Influenced the Quality-Assurance Strategies

As discussed above, a technology driver cannot influence all categories of advanced LSI technology and the associated management practices. Technology drivers coupled to large-scale memory principally influenced process development and high-volume manufacturing requirements. But these do not significantly interact with the principal quality-assurance issues raised by large-scale logic devices.

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[70]"Current Status and Problems of IC Production Facilities" p. 3. (Author unknown.) Paper submitted to Ohmi conference on Super LSI Ultraclean Symposium, No. 6, Tokyo, Japan, June 1988.

The quality-assurance issues for semiconductor firms posed by increasing complexity of logic ICs generated a different set of quality-assurance issues for semiconductor producers. We will identify the major ones from the Japanese viewpoint after explaining the primary focus the Japanese semiconductor producers have taken in logic product technology.

For many of the major Japanese semiconductor producers, their primary strategic focus has been on a segment of the logic market called application specific ICs (ASIC). The Japanese tend to define an ASIC-type product in very broad terms: all VLSI logic products, including gate arrays, standard cells, ROMs, application-specific processors, and general-purpose processors. Currently, though, the term primarily refers to gate arrays. This market raised new competitive issues for the Japanese producers, including developing new forms of customer interfaces and the mastering the manufacturing elements of real-time, variable production--i.e., reduced lot sizes with an emphasis on fast turn-around from final design to "first silicon" or first production lots.

Some of the major quality-assurance issues posed by the ASIC market place include:

- Problems with identifying defects: "The means of handling defects that manufacturers have difficulties in detecting and reproducing is posing a major problem...Such defects are found in larger number in ASICs than in other logic LSIs. In many cases it is impossible for manufacturers to reproduce the defects..."[71]

- Pressures to decrease qualification time[72] yet increase the reliability of devices: "Qualification tests require a great deal of time...Office automation (OA) manufacturers, etc. want to mount new LSIs on electronic equipment promptly in order to put new products on the market as early as possible. The fact that qualification tests require so much time is in conflict with this growing demand of manufacturers..."[73]

- Increasing difficulty in devising efficient test routines: As the complexity of logic devices increases, it is difficult--in a growing number of cases for very large-scale logic devices, impossible--to devise algorithms that test all routines; in addition, the time to test large-scale logic devices is increasing significantly. This makes it difficult to identify all failure modes and to reproduce failures when they occur.

While we do not go into these particular issues of quality assurance further, we believe these aspects of quality assurance--especially the issue of service quality, i.e., support

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[71]Nikkei Electronics, op. cit.

[72]As will be explained below, some customers, principally OEM computer manufacturers, require device producers to "qualify" their parts. This can mean a test period ranging from three to 12 months in duration during which the computer customer subjects a test lot to various electrical and mechanical tests and, in some instances, reviews the manufacturing process steps to qualify the fabrication line.

[73]Nikkei Electronics, op. cit.

for customer design and application--are becoming more important in the semiconductor industry.

C.2 External Influences Over Quality-Assurance Practices

One of the major factors influencing differences in the approaches taken to quality assurance between Japanese and American semiconductor firms has been differences in their relationships with upstream and downstream firms. The type of coupling between vendor and customer (and the type of market the customer is serving) as well as the coupling between device manufacturer and supporting equipment and material vendors influences the device producer's quality objectives and how efficiently and effectively they can be reached. This section discusses the general issues related to the upstream and downstream relationships. We will examine how these external relationships impact specific QA strategies in Japan and the U.S. in Sections D and E respectively.

Organization of End-Markets for Memory Circuits

The U.S. and Japanese semiconductor firms tend to face end-market demands that are very different in their structure. In turn, this influences the set of customer-driven quality

standards that the respective sets of producers face in the market. With respect to memory circuits, one difference is that on average over the past several decades, somewhere between 5 and 10 percent of the value of U.S. merchant semiconductor output has gone to the military systems end-market. Until very recently, Japanese producers had no comparable government end-market.[74] In the case of computer systems end-markets, there are only three U.S. merchant producers[75] of dynamic random access memories (DRAMs) today, down from perhaps a high of 15 separate merchant firms in the late-1970s. Meanwhile, in Japan the number of DRAM producers has expanded over the past decade to include all of the nine largest Japanese semiconductor producers.

These two asymmetries in end-market structure--U.S. firms having a military end-market to support while Japanese firms have a major lock on a key computer memory market--have had an impact on the quality strategies used. Historically, it was the

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[74]As Japanese device technology has become more advanced than U.S. technology in selected areas or has a better performance/cost aspect, U.S. suppliers of electronic assemblies to major military prime contractors have been incorporating Japanese components into U.S. military systems. This, more than the creation of an indigenous government market, has led Japanese device producers into the government segment of the semiconductor end-market.

[75]"Producers" refers to both performing design and full manufacturing.

military end-market that influenced U.S. quality strategies[76] while in Japan their quality strategies were driven by the requirements of high-volume memory.

The major American semiconductor firms have seen a change in the end-markets, which have played the leading role with respect to quality assurance over the past 10 years. At the end of the 1970s, it was the military end-market in parallel with the requirements of a select number of computer systems-makers that shaped the leading-edge quality-assurance practices for U.S. device-makers. As American firms withdrew from the computer memory market, the military end-market was left as the key from a QA standpoint. As the military end-market increasingly lagged commercial practices in the application of microelectronics technology, it had a decreasing degree of influence on industry practices.

By the late-1980s, two new markets emerged as major quality-assurance drivers for U.S. semiconductor firms. The first was the U.S. automotive end-market--particularly Ford[77]--and the

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[76]The role of the military with respect to quality has clearly shifted in recent years. This will be further elaborated on later in this section.

[77]For example, "Ford sent its quality people into Intel and trained engineers, manufacturing, quality control, and, yes, purchasing, in the techniques that Ford required from top suppliers. And, since Ford asserted that it already was getting

second was the Japanese market. These points will be further discussed further below.

The Japanese producers' push into semiconductor computer memory markets in the 1970s increasingly brought them into contact with a set of customers, namely the large computer systems companies, that had the most demanding requirements for quality assurance. That is, across all the various categories of end-demand for semiconductors, it was the computer systems houses--especially in the 1970s and early-1980s--that were setting the most demanding standards for quality assurance in the marketplace. They operated their own qualification processes that took anywhere from three months up to as long as one year to complete. These qualification processes provided the Japanese producers with information on failure mode analysis that exceeded their own internal capabilities. Thus, from the quality-assurance standpoint, the computer memory market was unique. In driving their organizations to meet the demanding requirements of U.S. (and later their own) computer systems operations, Japanese device producers significantly benefited from the close relationship to the computer systems houses.

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the kind of quality required from its other suppliers, Intel management had no choice but to accelerate its quality improvement goals." Purchasing, August 17, 1989, p. 74.

Growing Influence of Equipment and Material Inputs on Quality in the Semiconductor Industry

The evolution of the device and processing technologies generated a requirement for greater control over the process itself. Those defects that would create a defective device while still in the manufacturing stage had to be not only few in absolute numbers, but also smaller in size due to the reduction in the minimum feature sizes of the devices being processed. In the LSI era, the overwhelming sources of particulate contamination during wafer processing were people and the general ambient conditions of the clean rooms in which wafer processing took place. (See Table 9.3.) Throughout the 1980s, these two sources of particulates grew to be less and less important. "The generation of foreign substances cannot be completely controlled solely by improving the degree of cleanliness of clean rooms."[78] Today, the principal sources of contamination are the equipment and the materials (especially the so-called consumables--gases and chemicals)--by one estimate over four-fifths of the sources of contamination are accounted for by these two areas.

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[78]Nikkei Electronics, op. cit.

Table 9.3

Source of Particulate Contamination
(Percent)

	1980	1985	1990
Personnel	40	30	10
Ambient	40	20	10
Equipment	10	30	40
Gases/Chemicals Water	10	20	40
Total	100	100	100

Source: Toshiba

While both U.S. and Japanese firms foresaw the changes indicated in Table 9.3., it was the Japanese who recognized the implications of those changes on quality assurance. In the case of clean-room technology, the Japanese recognized that "with the manufacture of microscopic-sized LSIs, defects arising from unclean manufacturing equipment have gradually appeared...Foreign substances are mainly introduced by unclean production equipment and consist of dust generated by such equipment. It is very difficult to reduce the amount of foreign substances."[79]

Another aspect of the quality-assurance equipment linkage noted by the Japanese was the requirement for increases in the

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[79] Nikkei Electronics, op. cit.

mean-time-between-failure (MTBF).[80] This point was discussed in a paper by NEC: "Semiconductor production is extremely dependent on the quality of equipment. The quality of the finished wafer is, therefore, directly linked to the quality of the production equipment."[81]

Likewise, with respect to materials, Japanese device companies began setting goals for impurities and delivery conditions that placed significant pressure on vendors to excel. In some instances, for example, specifications for levels of impurities in certain chemicals exceeded the capability of existing measurement technology to measure impurities to the level specified by the Japanese firms.

C.3 Summary

The difference in the selection of a technology driver combined with differences in end-markets has influenced the development of quality-assurance practices in Japan and the U.S. The major Japanese semiconductor firms have, by and large,

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[80] Other measures of equipment reliability frequently cited are the mean-time-between-assists (MTBA) and the mean-time-between-repair (MTBR).

[81] Paper prepared by NEC, Yamagata facility management discussing total preventive maintenance concept at Ohmi Conference on Super LSI Ultraclean Symposium, No. 6, Tokyo, Japan, June 1988.

focused on DRAMs as their technology driver. This translates into an emphasis on process development and high-volume manufacturing. This, in turn, led the Japanese to broaden their ideas about what quality assurance demanded. That is, they started looking carefully at the supplier contribution to quality and began to drive their suppliers to achieve levels needed for the high-volume production of ULSI level devices. American firms started pushing hard on this aspect of quality relationships well after the Japanese.

D. Japanese Semiconductor Firms' Approach to Quality Assurance

It is the Japanese choice of a manufacturing business strategy that influences how quality assurance is applied in Japanese semiconductor firms. The one element of a manufacturing strategy that cuts across both strategic and tactical issues--i.e., reflects long-term decision-making yet also must be reactive to short-run requirements--is quality. This characteristic of the quality element led to two Japanese views on integrating quality into their corporate strategy:

- First, the fact that quality was seen as an element of a manufacturing strategy influenced the way they defined the goals for quality improvements. "Delivered ICs should be 100 percent quality products and claims of dissatisfaction

with [systems using the ICs] should be zero..."[82] The goal of zero defects is clearly coupled to manufacturing-related objectives: "Improving quality means improving yield and reliability."[83] Other Japanese presentations on quality objectives will also speak of the need for 'zero defects' and 100 percent yield and then relate these goals back to manufacturing issues." To cite two examples:

-- "The approach for 'zero defect' and 'securing yield absolutely' begins with thorough facility management. In order to use facilities in stable conditions, enforcement of cleaning of facilities, inspection, strengthening of maintenance services, and education of operator and maintenance staff in new phases is needed, which is producing good results. Needless to say, united activities of development, facility and production sections are the premise for 'zero defects'..."[84]

-- "In order to improve the quality of products and operate the production system efficiently, zero breakdowns and zero defects must be the goal."[85]

- Second, in order to attain these goals, the Japanese took a comprehensive view regarding the factors that influenced quality in the context of manufacturing operations. That is, they looked at quality assurance as involving every aspect of their organization from management decision-making to operator training to external relationships with vendors and customers.

It is the integration of quality into the Japanese business strategy has two aspects to it. The first is an organizational

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[82]"Total Production Maintenance," NEC, 1988.

[83]NEC Yamagata, op. cit.

[84]Author unknown, "Current Status and Problems of IC Production Facilities," paper prepared by Fujitsu semiconductor executive at Super LSI Ultraclean Symposium, No. 6, Tokyo, Japan, June 1988.

[85]"Total Production Maintenance," NEC, op. cit.

question: How are the Japanese firms organized to address QA issues? In Japanese firms, while there may be a staff group or quality-assurance department, the Japanese take a broader view of quality responsibilities, and this makes questions of formal organizational structure less important. The second part of this section deals with a management issue: How is the business strategy with respect to QA actually implemented? We start the discussion by looking at how quality fits into the overall strategic directions of the Japanese semiconductor firms that are driven by their manufacturing capabilities. In the final part of this section, we look at the current management approach taken in Japanese firms--a total approach to quality--and how it is actually carried out in practice.

D.1 Quality in the Overall Operating Philosophy of the Japanese Semiconductor Firms

In the early-1980s, both U.S. and Japanese firms targeted quality in terms of reducing the PPM product defect levels. Today most Japanese semiconductor firms (and many American semiconductor firms as well) have gone on to a broader concept that includes recognition that quality spans all aspects of the business from management decisions to customer and vendor interfaces. Usually the term "Total Quality Management" or TQM is applied to this broader concept. In the Japanese context,

there are really two aspects to it. One aspect has somewhat of a showcase element to it. But behind this facade lies a second, more serious aspect where the concept has had a meaningful impact on how the Japanese semiconductor firms view quality assurance and integrate it into their overall business strategy.

Currently, there is a broad push in Japanese businesses toward demonstrating that they subscribe to and apply the TQM philosophy. The idea is that a company needs to have the entire organization sensitized to the need for and involved in the production of quality product.[86] Again, this general push to promote the concept of TQM stands as a backdrop to the particular management practices that exist in the Japanese semiconductor industry. The idea of calling a quality-related program a "Total" type of system seems to have developed gradually in Japan over the past six to eight years. Japanese firms winning the prestigious Deming Prize seem obligated to demonstrate that they are applying a "Total" approach to quality assurance in order to win the prize. This is the showcase aspect of the TQM-type push. What the TQM approach means in actual practice is really nothing

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[86]The TQM-type of concept is not especially unique to Japanese organizations. For example, in a speech by Dr. Bob Thomas, special assistant to the chief of reliability at Rome Air Development Center, reference is made to Total Quality Management (TQM), which is essentially the same concept as defined by the Japanese managements. (See <u>Electronics Buyers' News</u>, July 31, 1989, p. T4.)

more than classic business-planning techniques being used to integrate quality-related goals into the business plans of the organization.[87]

One needs to be very careful to recognize the role that these types of general themes play for the Japanese organizations. For example, many Japanese firms will point to the fact that they have a staff to implement TQM that is organizationally reporting directly to the company CEO. But CEOs in Japanese companies do not always have clear operational authority. Rather, in some instances at least, they play a more figure head, representational role. Having the TQM staff report to the CEO suggests that it may be in part window dressing for the benefit of the outside world--a means to demonstrate that a particular company is really sincere in its quality-assurance efforts.[88]

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[87]See, for example, the discussion of TQM's implementation at NEC IC Microsystems in Look Japan, September 1989, p. 37. Goal setting is defined as the first step of the process; education of the work force regarding the goals along with providing them with the tools to carry out new tasks are covered along with the establishment of TQM organizational infrastructure to provide an ongoing monitoring of goals versus outcomes and to generate feedback into the organization.

[88]In Japan, being truly sincere about one's efforts is especially important.

Stating this does not mean that the organization does not, in fact, aggressively and continuously pursue quality improvements, but more often the real authority to drive quality improvements would reside at the factory manager level of the organization--especially with the mid-level managers. But as demonstration to the Deming prize reviewers, who critique a company's QA policies, it may be necessary to have a TQM staff and that staff needs to report to the CEO level in the organization.[89]

The aspect of the TQM movement that has operational content for the Japanese semiconductor industry is the implementation of something they call "Total Productive Maintenance (TPM)."[90] The relationship between TQM and TPM was described as follows:

> "The number of corporations which develop TPM as a part of TQC has been increasing. Both TQC and TPM execute maintenance and improvement of quality and have the same purpose of aiming at 'improvement of atmosphere of corporations,' but TPM's mission is to advocate the idea of

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[89]This view is consistent with the way the Deming Prize examination categories are given weight; according to one study, 60 percent of the weight falls on processes versus 40 percent for results. "...the Deming prize tries to give priority to whether the individual company creates it own Total Quality Control system." S. Shiba, "Universal Quality," op. cit., p. 33.

[90]This concept is promoted by yet another association, the Japan Plant Maintenance Association (JPMA). The concept was developed in the early-1980s with the most frequently cited source being S. Nakajima, TPM Development Program for Production Information, Japan Plant Maintenance Association, 1982.

TQC, whose supremacy lies in quality, is more concrete and creates an atmosphere which produces quality on the production floor [emphasis added]."[91]

Pursuing an approach to quality that emphasized enhancing the effectiveness and efficiency of manufacturing was a clear outcome of the focus that Japanese semiconductor operations had on pursuing a manufacturing-driven strategy. The history of TPM was summarized as follows:

"...Preventive maintenance started in America. Before 1950, when breakdown maintenance was common, repair work was done only after equipment failed to function. The concept of performing Preventive Maintenance (PM) before such breakdowns occurred took hold after 1950, and got a new twist in Corrective Maintenance (CM), which sought to correct problems before they caused a breakdown. Later, Productive Maintenance came into being, and was performed to maintain high productivity. In the 1960s, Maintenance Prevention, applied during the planning stages, was introduced, in which considerations for reliability, maintainability, and cost efficiency were built into the design.

In the 1970s, we entered the TPM age. This concept incorporated American Productive Maintenance methods into one suitable for Japanese corporate culture. The result is one that respects human value and utilizes everyone's participation for total efficiency..."[92]

What did these "total" QC and "total" productive maintenance concepts mean in the Japanese management sense? There are

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[91]H. Horikiri, LSI Production Headquarters, NEC, "Current Status and Problems of Production Systems," June 1988, p. 8.

[92]"Total Productive Maintenance," op. cit.

several things that it did not mean. It did not mean that job descriptions of managers or operators were formally rewritten nor did it mean that managers' performance bonuses were determined on a new set of criteria that gave greater weight to quality performance. That would have been the type of change recorded in the West. It did not necessarily translate into specific quantifiable goals. Rather, collectively, the organization understood that any action that resulted in quality improvements--measurable or not--was to be carried out. As a whole, the process is more intuitive, less formal than would occur in an American organization.[93] The discussion in the next part looks at how the Japanese took on one dimension of quality assurance with a comprehensive, "total" approach--the issue of maintaining yields for larger-scale LSIs.

D.2 Implementation of the Japanese Quality Strategy

All major Japanese semiconductor firms by the mid-1970s were applying statistical process control methods to controlling the

[93]Contrast the less formal approach of the Japanese to the following statement by an AT&T executive: "It is vital that all project managers define specific, measurable quality goals for their projects." Statement of John Mayo, AT&T Bell Laboratories, Executive Vice President, Network Systems, in Quality By Design, A Quality Manual for the AT&T R&D Community, op. cit., p. 15. We should note that there is nothing incorrect about the statement, per se, rather it makes an interesting contrast in management techniques and style to those found in the Japanese context.

individual process steps in fabrication and assembly operations.[94] The application of these techniques had been pioneered at AT&T in the 1950s.[95] "In Japan, the manufacturing group was the strongest member of any company as evidenced by the success of statistical process control in manufacturing."[96]

Management disciplines needed to effectively apply SPC techniques were already well embedded in Japanese management culture. These would include, for example, process engineers working to incrementally refine process steps in a disciplined, systematic way; rigorous correlation through customer feedback of the occurrence of defects to specific process steps; training programs for operators to increase their understanding of technical issues in fabrication and testing,[97] and so forth. In other words, aspects of quality assurance that American firms

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[94]Statistical Process Control is defined as: "The application of statistical methods to analyze data, study, and monitor process capability and performance. Through the use of SPC methods such as control charts, you can determine if a process is in control and then keep it in control while working to achieve a new level of process performance." Source: Process Quality Management & Improvement Guidelines, op. cit., p. 99.

[95]A major reference on SPC remains the AT&T Statistical Quality Control Handbook, 2d ed., 1958.

[96]K. Kurokawa, "Quality and Innovation," op. cit., p. 6.

[97]Greater stability of the Japanese operator work force facilitated making these investments in operator training because individual companies could expect a reasonable rate of return on such investments.

were to more widely and rigorously adopt in the late-1980s were already well-practiced disciplines observed in the Japanese firms a decade earlier.

Further, the Japanese firms by the early-1980s were already taking a more comprehensive approach to quality assurance. As an example of their more comprehensive approach, consider the Japanese view of the seemingly mundane step of sawing the wafer into individual die: The Japanese memory producers in this period were more conservative in laying out the die on a wafer--that is, they would accept a lower number of die per wafer in order to have greater spacing between the die so that in the wafer-sawing operation there were fewer die that had chipped edges. Chipped edges may or may not have led to a mechanical or electrical defect, but the Japanese believed, at a minimum, that it resulted in a cosmetically better product if the edges of the die were undamaged. To put this seemingly simple concept in practice required integration of the knowledge of wafer-sawing technology all the way back into the original steps of laying out the chip design and wafer mask. This is typical of the kind of comprehensive approach to end-product quality that typified the Japanese management view--even a decade ago.

The next iteration or addition to Japanese quality-assurance strategies was to integrate the TQM approach that was becoming

popular in Japan in the early-1980s. To some degree, TQM was simply a more formal approach to the types of management practices already undertaken throughout their organizations.

The best way to see what TQM means is to focus on how the Japanese firms translated this general concept into actual management practices targeted to increase yield. With all the major Japanese semiconductor companies utilizing DRAMs as their principal technology driver, a central issue of quality assurance, as noted above, was achieving and maintaining high yields. The Japanese tied yield improvements to programs in four areas: (1) problems in processes; (2) defects of circuit design and patterns; (3) low degree of technical skill (of operators and technicians); and (4) bad condition of equipment. The next two parts describe the specific practices the Japanese managements pursued in these areas to gain greater leverage with respect to quality assurance.

Influence of Technology Driver on Internal Japanese Quality Organization

The issues of achieving higher yields and sustaining yields at a higher level for DRAMS led to a focus by the Japanese on three aspects: operator training requirements; automation in

fabrication lines; and improvements in equipment reliability. Each is discussed in detail:

<u>Operator Training Requirements.</u> The Japanese managers, as a general rule, have a higher degree of confidence in their fabrication operators than American managers.[98] In a Japanese-managed front-end, operators are expected to perform a number of tasks that would be left to engineering technicians in a U.S. operation. Equipment assists, for example, and adjustment to equipment operating parameters are under the jurisdiction of the equipment operators. With well-trained and well-disciplined operators, Japanese semiconductor managements do not see the need to move rapidly toward a peopleless fab. With strict personnel management and training programs in place, the problem of reducing particulates and maintaining yields shifts to one of material reliability--better material in the process.

The Japanese semiconductor firms have over the last several years sought to expand the job responsibilities of the line operators. This has taken on two dimensions: first, broadening the responsibilities within the traditional job definition as an equipment operator, and second expanding the job definition to

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[98]Observation based on author's interviews with Japanese semiconductor executives and discussions with American semiconductor executives.

encompass a broader set of responsibilities, principally in the area of maintenance.[99] The following statements by Japanese managers amplify on these two points:

- "...it is a matter of course that the first step of maintenance lies in the operator because there are many incomplete [in the sense that the manuals or the equipments themselves do not cover all states of] IC production equipments and the skill of the operator is indispensable. Therefore, the current status seems to indicate that methods which [assist] necessary specialization and expansion of ways and the education to make it possible is indispensable."[100]

- "The greatest effect of TPM was in the improvement of human factors. This means that operators could gain capacity to do self-managed maintenance and maintenance personnel gained the ability to maintain mechanical equipment. Furthermore, the production technician could develop design capacity for equipment that requires little maintenance...We were able to increase value-added productivity, reduction of accidental failure, increase in operation rates of equipment, reduction of low process rates, reduction of defect claims from customers, and reduction of maintenance expense, reduction of inventory, elimination of hazards and pollution, can be expected. Further, as a nontangible effect, self-managed control was enhanced so that the operators' viewpoint changed to one where they maintained the equipment independently. Also, elimination of defects and breakdowns became a reality...and the corporate image was enhanced."[101]

- "Existing QC circle activities were not conducive to full involvement because of stereotyped thinking patterns about

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[99]Or to transition personnel from production into maintenance.

[100]"Current Status and Problems of IC Production Facilities," op. cit., p. 5.

[101]"Total Productive Maintenance," op. cit., p. 28. This discussion could form a more explicit definition of quality objectives for the Japanese semiconductor industry.

the working system. In terms of the relationship between operator and equipment, even though they called the operator "the subject of preventive maintenance," it was only words. They still thought "I am the one who makes the product and you are the one who repairs equipment." Because of the introduction of TPM working system, the negative way of thinking about responsibility, as mentioned above, was eliminated. We clarified the expected level of accomplishment for every step of self-managed maintenance, and then increased the practice and the training to meet that level. As a result, improvement in the area of the six great losses and remarkable improvement in safety was obtained. The six great losses are: failure loss, maintenance loss, short-term stoppages, speed loss, repair loss, and restoration loss."[102]

- "As higher knowledge and skills are required of maintenance staff, the work of an operator gets simplified, and putting operators in charge of several systems and expanding their work sphere accelerate the simplification."[103]

- "So long as the current TPM activity is an activity which revolves around people, it is needless to say that educating staff is most important. In the future, a good portion of these activities will be done by machines due to the desire to reduce manpower. Even so, people will remain as the nucleus. Therefore, if we think about the details of education, currently mainly special skill education are enforced, but expansion of those is needed. Moreover, computer education for factory automation of facilities would be necessary too. Further, it will be more and more important to improve quality of products through maintenance and management of facilities. So it is necessary to expand process diagnosis education to the lowest personnel levels."[104]

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[102]"Total Productive Maintenance," op. cit., p. 16.

[103]"Current Status and Problems of IC Production Facilities," op. cit., p. 5.

[104]H. Horikiri, op. cit., p. 8.

Automation on Fabrication Lines. The issue of why and how to go about automating semiconductor fabrication lines illustrates fairly well the difference in management viewpoints that exist between the Japanese and American semiconductor managements. The American view on the objectives of automation is somewhat different than the Japanese. American management views automation principally as a means to achieve cost improvements. Indeed, according to an American speaker at a conference on automation of semiconductor fab lines, automation would not take place if there were no direct impact on production costs:

> "Automation of wafer fabrication will not succeed unless the cost to produce the semiconductor product is reduced through automation."[105]

Manufacturing cost reduction is not the principal goal of Japanese managers from automation of front-ends. Indirectly reduced costs may and probably will happen, but they are not usually identified as an explicit goal. The Japanese are automating their front-ends for reasons partly related to requirements of the technology evolution to ULSI requirements and partly for reasons related to quality assurance--better

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[105]M. Shopbell, "Equipment Automation," Information Services Seminar, SEMI, 1985, p. 239.

processing control, materials handling, data processing, and decision-making.

In the case of memory, the Japanese managers do not believe the 16-Megabit generation of DRAMs can be produced without new automation. Thus, they are introducing "soft" automation (information for decision-making) and equipment automation stage-wise into the 1-Megabit fabs in order to attain the levels of particulate control they see as essential as they build 16-Megabits. In the ASIC area, the automation drive is heavily oriented toward reducing turnaround time--a key competitive element in the new type of customer-vendor relationship that the ASIC market demands. This illustrates a different thrust of the Japanese management philosophy. The Japanese set engineering goals and expect the results to in turn lead to a superior cost position and such benefits as:

- maintenance of appropriate processing records for each wafer in order to perform real-time process control and better correlation of lot history to test data or failure data analyses.
- elimination of downtime to achieve better utilization. Presently, fabrication lines are too difficult to balance for effective automation at least on the technical side of the fab area. The reasons for this are manifold but the most important reason is unscheduled equipment downtime. Others include set-up time, scheduled downtime, and balance variation from one piece of equipment to the next; and

- greater integration of marketing and manufacturing. The ultimate goal for automation is to automate the complete marketing process that ranges from order processing to shipment and support of the product in the field.

The following statements illustrate how the Japanese managements view the coupling between quality assurance and automation:

- "Three elements were accomplished in the production line implementation [of CIM] to achieve high quality and high yields [of BiCMOS] IC chips: (1) high degree of cleanliness in the manufacturing work area which is essential for MOS processing; (2) precision and attention to detail in process control; and (3) precision control in the third dimension, a factor demanded in bipolar realized by using short lead times and developing protocols for increased energy conservation."[106]

- "It has been approximately three years since Factory Automation (FA) system started operation [in the Mitsubishi Saijo plant, the world's first entirely automated semiconductor front-end], and the effects shown below resulted: (1) the quality of product improved; (We were able to eliminate the use of people--the cause of dust, which greatly affects yields of super LSI--by introducing automatic transport, and decrease damage due to dust, which attaches to a product or handling mistakes. Moreover, we were able to prevent problems and maintain stable quality levels by collecting results of QC information and feedback and feedforward control in real time.) (2) production time was shortened...; and (3) a reduction of manpower was achieved..."[107]

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[106]T. Andoh and H. Sawazaki, "The CIM Concept Directs Toshiba's BiCMOS Mass Production Line KUBIC-II," Semiconductor World, February 1988, pp. 45-47.

[107]Ryo, Uehara, et al. "FA System in Semiconductor Plants," Mitsubishi Electric Technical Bulletin, April 1987.

- "The most direct effect of automation is some manpower savings, but mostly improvement in quality and yield and reduction in steps in IC production process. Fluctuations in yield is great in the IC production process, and it affects product cost greatly. Among factors which affect yield, there are many to be solved by automation. Especially hoped for are improvements in reproducibility and elimination of defects due to worker error, which are long-lasting problems."[108]

<u>Improvements in Equipment Reliability.</u> As discussed in Section C, Japanese semiconductor managers see a close coupling between improvements in quality assurance and requirements for greater equipment reliability. For example:

- "...we have to have a countermeasure regarding the elements which control yield, especially for the problems surrounding the equipment. To ensure proper equipment standards for the production of a good quality product, the following elements are important: (1) preventive maintenance design for the plant and equipment; (2) improvement of technology and skills for using the equipment; (3) [operator] mastery of equipment; and (4) renovation of peculiar technology capabilities."[109]

- "The concept of Maintenance Prevention (MP) design means activities to decrease problems, losses due to deterioration, and maintenance costs. This is achieved by fully checking reliability [of equipment], ease of maintenance, economics and safety based on maintenance information gathered through independent maintenance, individual improvement, and so forth of existing equipments...We need to determine objective values for each item of equipment for each facility and plan in such a way that those values are achieved during the design stage. It

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[108] "Current Status and Operation of IC Production Facilities," op. cit., p. 2.

[109] "Total Productive Maintenance," op. cit., p. 7.

is necessary to take care to make a design which pays attention to dust levels, especially in facilities used for wafer processing."[110]

There is also an interest in decreasing the time it takes to ramp up a new production facility to full-volume production. Some Japanese firms want to achieve a "perpendicular start-up," which puts pressure on equipment performance.

"Circulating management at an early stage is an activity which plans stable operation from the start by debugging poor conditions at the same time that products are actually being produced after completing set-up, adjustments and test runs. During this phase, checks are done not only of basic equipment performance, but also of details, including the maintenance prevention design. Poor conditions are detected and countermeasures are worked out against them...Test runs normally need a period of one to two months, but we have to shorten this time and aim at perpendicular start up in order to hasten full-scale mass production and recover our investment."[111]

The issue of achieving higher equipment reliability is also addressed in the next section discussing the coupling between equipment vendor and device producer in Japan.

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[110] H. Horikiri, op. cit., p. 7.

[111] H. Horikiri, op. cit., p. 7.

External Relationships and Their Influence on Japanese Quality Strategies

Among the areas where external relationships in Japan have led to differences in quality-assurance practices, two are especially important to understand in detail: the more extensive feedback of quality-assurance data from customer to semiconductor vendor (and its application by the vendor to resolve the problem); and the closer coupling between device producer and equipment and material vendors in Japan. It should be noted that the differences in practices in these two areas are not absolute--that is, the same relationships exist among U.S. firms, but not as frequently nor to the same degree.[112]

More Extensive Feedback Loop Between Device Vendor and Customer. In order for vendors to understand whether they are meetings customer needs and expectations (see Section B, definition of quality), the Japanese customers and their vendors "...establish a feedback cycle treating the suppliers and users

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[112]It should also be mentioned that there are characteristics of the Japanese business culture that also foster tighter working relationships among different business entities. For example, if the two firms were members of the same keiretsu, they would more readily exchange information. There is a large body of information on these general Japanese business organization traits. See, for example, James C. Abegglen and George Stalk, Kaisha, The Japanese Corporation (Charles Tuttle, Tokyo), 1985.

as one body rather than have them in confronting positions."[113] There are several aspects to this feedback process.

One aspect of the feedback process is an aggressive policy on the part of customers to measure quality and communicate the results of their investigations to vendors. In some instances, Japanese customers analyze good units in order to identify potential defects:

> "It is said that 'inspection does not improve quality. Good quality is produced in the manufacturing process.' Therefore, [systems] manufacturers would like to have the parts manufacturers produce perfect products rather than having to eliminate defects when they carry out inspections. Information concerning quality evaluation from user's point of view should be fed back to, and be made the best of by the part manufacturers."[114]

Second, there is a growing realization that even good products--in the sense that they were acceptable at all stages of manufacturing by the vendor and passed all tests by the purchaser--are a growing proportion of the total product failures. "In other words, the products are actually acceptable. Defects, if they exist, cannot be detected in the products rated

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[113]Fujikawa, et al., "Evaluation on the Quality of Semiconductors from the Users' Point of View," June 1982, Quality Engineering Department, Engineering Division, Matsushita Communications Industrial Co., Ltd, p. 14.

[114]Fujikawa, op. cit., p. 2.

acceptable."[115] Defects in some instances can only be reproduced once the product is mounted into a board subassembly or in the entire system. In this case, "in order to cope with defective products, therefore, users and manufacturers must cooperate."[116] Also, an increasing proportion of total defects are not reproducible--at least one-quarter or more of total defects fall into this category.[117]

A third aspect of the feedback loop was the close relationship that the Japanese firms developed with U.S. systems producers. We noted in Section C the difference in end-markets served and the role the qualification process at systems houses played in putting Japanese producers in touch with the most demanding segment of the customer base from a quality-assurance standpoint.[118] The role that DRAMs play as a quality driver, especially for manufacturing practices, and the benefits of the coupling to major U.S. computer systems houses can be noted in the following statement:

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[115] Nikkei Electronics, op. cit.

[116] Nikkei Electronics, op.cit.

[117] Nikkei Electronics, op. cit., Figure 4.

[118] In Japan, a growing number of firms outside the computer systems segment of the market are installing quality-assurance programs and qualifying vendors. This is a fairly recent occurrence. In the U.S., as will be discussed later in this section, it has been the automotive sector that has become especially important in driving quality-assurance practices.

"LSI manufacturers distribute samples (of new generation DRAMs) for evaluation of electrical characteristics to mainframers which are the largest LSI users, more than a year before commercial production is started. 'We must feed information on convenience of use back to the manufacturer' (statement of Nippon Digital Equipment). LSI manufacturers repeatedly modify new memory LSIs (including mask design) based on the results of users' evaluation. Such modifications are made during the period extending from the use of samples for evaluation, through qualification testing, to the early stage of commercial production...Users are superior to manufacturers in failure analysis. U.S. IBM, for example, found the stress migration in Al wires in the 64K DRAM...Mainframers use only qualified products...The qualification system of office automation and control equipment is not as strict as that of mainframers."[119]

Closer coupling between device producer and equipment and material vendors. The Japanese relationship with their vendors must be understood in the context of Japanese business hierarchial relationships.[120] The vendors are considered to be essential extensions of the manufacturers' capability to sustain and improve quality. Given that, there are a several aspects of these relationships that go beyond the degree of integration observed in the U.S. With respect to equipment vendors, there is an extremely tight coupling. This means that, for example, the device firms call upon the equipment firms to aid them with technical support in all phases of manufacturing--including

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[119]Nikkei Electronics, op. cit.

[120]We already noted at the beginning of the section the need to understand general characteristics of Japanese business relationships.

during the sensitive stages of developing new processes.[121] The following information on relationships between equipment firms and semiconductor manufacturers, based on a survey of 29 device producers performed by Tohoku University,[122] reinforces the view that a tight coupling exists:

- Over 15 of the respondents required "same-day response" to repair and service requirements; one company stated "under four hours."
- Most of the firms demanded service techs from equipment firms be assigned either on a permanent basis or make periodic visits. No respondent would accept visits on an "as-needed-basis" only.
- Of the 13 firms that responded to a question regarding what their policy was on the development of LSI fab equipment, eight indicated a joint development policy, four indicated total reliance on outside suppliers, and one firm indicated total reliance on in-house development.

While not clearly stated in the report of the survey results, it is highly likely that the larger Japanese semiconductor firms were the ones most demanding of high levels of service and support and also undertaking joint development of new equipment with equipment suppliers. The following discussion

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[121]Based on interviews conducted by the author in Japan with equipment vendors and semiconductor firms. Several equipment firms noted that they are never pressed to the same extent to supply information by American firms nor asked to work with the American firm to assess new process developments.

[122]Information provided to author by Dr. Ohmi of Tohoku University.

by one major Japanese semiconductor firm touches on all the points noted in the Tohoku survey and indicates how uneasy the Japanese firms are at allowing equipment vendors to operate at arm's-length:

> "As for the MTBF, there is a tendency for purchased equipment to be inferior...As for mean time between repairs (MTBR) of purchased products take longer among the same type of equipment. In MTBR, waiting time of maintenance staff, waiting time for maintenance parts can be said to be problems of purchased equipment. When the equipment manufacturer is in charge of maintenance, the waiting time of maintenance staff is long due to factors such as insufficient operation during days off and nights, and staff commuting time, although that depends on the maintenance system of the manufacturer. For countermeasures, establishment of maintenance systems directly connected with the plant of the equipment manufacturer and establishment of in-house maintenance system from the time the facility was introduced can be listed. The former has a limit due to the restriction of the area or number of facilities owned. What we have to pay attention to is acquisition of technological information from equipment manufacturers, which is the disadvantage of the latter method. Enforcement of periodic meetings is effective as the counter plan...Improvement of self-built facilities is practiced vigorously by technologies of facility related sections with the background of self-process technologies. This is advantageous for securing competitiveness."[123]

The second aspect of the relationship with vendors flows from the technology requirements of the ULSI era. Because most of the major Japanese firms use memory as their technology driver, they are focused on the equipment requirements of high-

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[123]Paper presented to conference June 1988 sponsored by Dr. Ohmi on improvements in quality in LSI manufacturing. Paper is believed to be presented by Toshiba executive.

volume manufacturing of ULSI devices. As discussed above, these requirements have led the Japanese producers to examine issues related to increasing the MTBF and, more recently, MTBR. In turn, to accomplish these objectives as well as to drive down the particulates generated by equipment, the Japanese are setting very aggressive standards for equipment vendors to meet.

The Japanese producers also maintain extremely close and demanding relationships with their material vendors. For example, the Tohoku University survey found that with respect to the location of suppliers for sealants, gases, and chemicals, Japanese semiconductor producers overwhelmingly indicated that they preferred to have the supplier co-locate with the plant being served. Two other aspects of the Japanese semiconductor producers' relationships with their material vendors that have an especially important influence on quality are, first, the development of specifications and, second, the ongoing, continuous monitoring of actual performance. Both elements are described in a report, prepared by the Semiconductor Industry Association of Japan, on evaluating Japanese relations with their material vendors:

> Specifications. "The first impression is that silicon specifications for U.S. and Japanese semiconductor-makers are by and large the same.

However, there is a definite trend toward tighter specifications [on the part of the Japanese] usually related to the device technology for which silicon wafers are used. Since the Japanese are leaders in memory technology and memory technology is pushing the levels of integration through lithography and process technology, the typical Japanese [specification] shows higher technical content. Examples identified are flatness, oxygen-induced stacking faults and lifetime measurements for the wafer.

A major difference, however, is how a specification is interpreted. In Japan, an acceptable level of product is where zero percent of the product exceeds the specification. [That is, the Japanese seek to keep specifications within the range of the guardband, or limits of the specification.] U.S. users usually accept the full range of the specification limit, measuring to a SPQL, where a defined percent of product out of limit is acceptable. As a consequence, product used by the Japanese manufacturers is typically identified by a narrow distribution well within the limits of the specification whereas the product used by the U.S. manufacturer usually has a much wider distribution with the tail possibly not exceeding the spec..."

Monitoring of vendor performance. "[M]any Japanese [semiconductor] manufacturers isolate suppliers lots during the manufacturing operation to allow a constant measurement of performance. There is no premium for good performance, but a drop in performance values (i.e., normalized yield) may lead to punishment by order cancellation if a trend develops. This effectively forces suppliers in Japan to perform to a higher standard, even though the specifications are the same. It also appears suppliers are now assuming initiative and responding by using tighter spec, as a form of competition. In some cases this has led to the expectation of normalized distribution within the narrower limits."[124]

[124] J. Freedman and R. Lerch, "Analysis of Specification Requirements of U.S. and Japan Semiconductor Fabricators," paper prepared for Semiconductor Industry Association Japan, June 2, 1987.

E. U.S. Semiconductor Firms' Approach to Quality Assurance

As was mentioned, the current set of quality strategies and practices at many U.S. semiconductor firms--in particular, among the "leading-edge QC" firms--is not that different from strategies and practices observed in the major Japanese semiconductor firms. Just five years ago, this would not have been the case. What triggered the changes? Certainly the March 1980 Hewlett-Packard disclosures of significant differences was one element. In the wake of these disclosures, U.S. firms began a concentrated drive to reduce PPM defect levels to achieve levels comparable to their major Japanese competitors. Today, all major semiconductor producers achieve PPMs below the 100 to 200 level.[125] Thus, for the leading-edge QC operations in the U.S., the changes in quality-assurance strategies have worked to reduce and, in some instances, eliminate the "PPM gap."

Among these leading-edge QC firms, the concept that quality is conformance to specifications and fitness for use is no longer accepted as the appropriate definition. Drawing on the responses

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[125]This statement is based on: (1) the Japanese assessment of their own level of PPMs; (2) the Semiconductor Industry Association military quality survey reported average PPMs; (3) interviews with U.S. semiconductor executives; and (4) interviews with executives in major U.S. systems houses. Note also that Hewlett-Packard now reports comparable PPMs for major suppliers from the U.S. relative to Japanese suppliers.

from the survey interviews, the first part of this section examines the current philosophy of defining quality. The next part then examines how these general concepts are actually implemented and integrated into the U.S. firms' operating philosophy--again, based on the survey analysis presented in Chapters 6 and 7.

E.1 Evolution of U.S. Semiconductor Managements' General Philosophy Regarding Quality Assurance

Up through the early-1980s, most U.S. semiconductor firms relied principally on inspection and verification methods to insure quality. Within the organizational structure of the firm, typically there was a classic quality-control organization with responsibilities for conducting inspections and auditing operations performance. In the wake of the Hewlett-Packard disclosures on significant differences between Japanese and U.S. quality levels, U.S. semiconductor firms began to reevaluate their philosophy on quality assurance.

Today, among the leading-edge QC semiconductor operations in the U.S., firms are either at the stage of prevention or beyond it into some level of applying a TQM approach.[126,127]

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[126]According to a survey of U.S. electronics firms conducted by the American Electronics Association, 91 percent of the firms surveyed with over $10 million in revenues indicated they employ

Based on the interviews with industry executives already discussed in Chapter 6, several changes have clearly taken place. First, there has been a significant shift in the quality philosophies of these firms that has taken place in the last five years. All of these firms indicate from their comments that they are applying part, if not all, of the key aspects of the Japanese quality-assurance strategy. For example, the use of SPC is now thoroughly embedded into their practices; customer and vendor relationships are looked at as part of the overall quality-assurance process; all management layers in the organization are a part of the process of quality assurance; management decisions are reflecting quality-assurance objectives, and so forth. The next part will look at this point in more detail.

Second, the value of quality as a competitive tool is changing. That is, all leading-edge QC firms must meet comparable PPM defect levels--these firms have been successful in achieving and sustaining that level of performance. Now the view is that strategic advantage to be achieved from quality assurance must come from other attributes of quality such as service

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total quality control. See Electronic Buyers' News, September 18, 1989.

[127]See the discussion of successive stages of quality-assurance philosophies in Chapter 6.

performance, etc. The following statements from our survey interviews indicate how U.S. firms view this issue:

- "Quality essentially is what the customer perceives it to be, and it is usually related to service. Service is becoming a key part of most programs."[128]

- "Some companies think that the key to gaining market share is in service quality now instead of product quality (everyone has to meet product quality). This is not necessarily true with the TPM approach. Quality cannot be broken down into process, service, etc. There are two types of quality: required quality and attractive quality. The only way to gain market share is to improve your overall total quality (which encompasses every aspect of the business), thereby going beyond the required quality."

- "It is easier to get line manufacturing people to embrace the idea of quality because their finished product is more tangible to them (due to measurement and controllability). It is a more difficult task, however, to get white-collar management (such as sales reps, product engineers, and design engineers) to embrace the quality concept because their jobs do not have the flow for tangible delivery of end-products. [We] are trying to put across the idea of quality not just being important in manufacturing."

Whereas in the Japanese firms there is a clear coupling of the quality-assurance process into manufacturing strategies, U.S. semiconductor firms are a far more diverse set with a wider variety of strategies. For example, only a small number of U.S. firms have their strategies tied to memory as their technology driver with its associated high-volume manufacturing imperative;

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[128]Statement attributed to Craig Walter, HP Quality Director, Electronic Buyers' News, September 4, 1989, p. 44.

some clearly have strategies keyed to dominance in microprocessor technologies; others are keyed to more specialized forms of product technologies such as analog or high-speed CMOS circuits.

Thus, given the greater diversity of overall firm strategies evident in the U.S. semiconductor operations, it is clear that quality-assurance practices will vary depending upon each firm's strategic goals. Thus, there is no inherent reason why all U.S. firms should pursue similar quality-assurance strategies. As one survey respondent stated: "Quality is part of a culture. Quality indices become tactical because strategy has too many concepts that tend to be visionary. A company should become tactical after it decides where to position its business. The position of the its business and customer base are influential."

E.2 Execution of U.S. Quality-Assurance Strategies

The evolution of quality-assurance strategies toward prevention was the step needed to drive PPM defect levels down to a level equivalent to the Japanese. But, as was noted in Section C of this chapter, the evolution of the technology combined with shifting marketplace requirements forced an even more complete integration of quality assurance into all phases of semiconductor operations--the TQM philosophy.

The leading-edge QC firms have all moved significantly toward or beyond the prevention philosophy of quality assurance. Some have moved to adopt and apply the more robust philosophy of TPM, while others have just begun to pick up pieces of the TPM-type philosophy. As the general management philosophy toward quality assurance in the major U.S. semiconductor operations evolved, changes reflecting the new philosophies occurred in their internal organizational structure and operating philosophy, as well as in their external relationships with customers and vendors.

Changes in Internal Organizational Practices

The requirement of lowering PPMs and of meeting growing requirements of customers for "total" quality assurance led to major changes in organizational structure and management decision-making. There were four elements that generally characterized these changes: (1) reorganization of the QC organization and redefinition of the mission of the QC organization; (2) responsibility for QC diffused throughout the organization (with changing job descriptions); (3) greater discipline applied to management decision-making, not only in manufacturing decision-making but also in design and R&D; and (4) SPC rigorously applied in all phases of manufacturing operations.

Reorganization. As the quality-assurance philosophy moved more toward prevention (and later including TQM concepts), the traditional QC line organization was decreased in size and its mission statement revised.

- "The quality systems audit group looks at quality assurance from a macro viewpoint. It reports to the CEO with responsibilities for defining sample procedures, audit to make sure processes are followed, that each operating group has a cohesive QC plan and that every step is followed..."

- "The product assurance group is responsible for worldwide reliability, monitoring and qualifying products and processes in wafer fab (information on reliability is collected but not as part of formal audit process), and monitoring and auditing the assembly groups. Reliability means setting standards and defining procedures for the operating groups to follow. The manufacturing groups have the ongoing responsibility of monitoring if the goals set by the product assurance group are being met."

- "The dependence on a classic quality organization has decreased. The job responsibility has shifted to operations. The quality organization has become responsible for auditing, acts a facilitator with a link to the customer, and essentially measures the effectiveness of the organization in meeting the corporate emphasis on quality."

Diffusing Responsibility. In conjunction with the change in the mission statement for the QC organization, responsibilities for quality assurance were diffused broadly through all parts and across all levels of the organization. This shift aligned the management decision-making culture more closely to the Japanese. However, the means by which it was accomplished was more formal. Job descriptions were rewritten and managers' performance bonus

scoring systems were altered to include an explicit quality-assurance element. The following statements taken from our survey interviews are illustrative.

- "Quality is [now] given a definitive weight for line people in terms of incentives and bonuses...Something like 10 to 20 percent of a bonus may be dedicated as a reward for quality, for effective implementation and use of SPC."

- "[We] have a minimum criteria [for quality assurance] that is a function of every part of the company. Objectives are shifting in all departments so that quality is a part of the performance definition."

- "[It was difficult] getting top management, and even more difficult at the middle management level [to get a mindset change toward quality assurance]. Question of what the mid-level guys are being rated on--their performance ratings. In the past, quality was not in their ratings--the managers know the performance items--if quality is not on the list, it would take a back seat--it's a mindset thing...[Today it's] in everyone's performance ratings (between 10 and 20 percent of his performance bonus is whether he made corporate quality goals, a large piece)."

<u>Greater Discipline in the Organization.</u> Japanese firms are considered, even by U.S. managers, to have a greater degree of discipline within their organizations. As one U.S. R&D manager summarized: "The U.S. [semiconductor firms do not] do a good job on incremental development. The Japanese [semiconductor firms] continually drive on yield and design...The U.S. discipline is getting better..."[129] Greater discipline means, for example,

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[129] W. Finan and J. Frey, op. cit., p. 110.

tighter control over process specifications and closer coupling between designer engineers and process engineers to ensure a product's design will optimize the process (i.e., yield and product performance) being run in the fab. Thus, greater discipline is an element of achieving long-run improvements in quality assurance.

To achieve greater discipline, U.S. semiconductor managements have had to change their management philosophy to "force teamwork and not allow independent actions." Walters of Hewlett-Packard notes: "The key is recognizing a quality issue wherever it arises, taking data on that issue and then using that data to guide you to a solution, instead of relying on genius alone to solve the problem."[130] Comments related to this issue received during our survey interviews on this point were:

- "There is [today] a tight control over operations--no "tweaking" of the process steps is permitted. If you don't approach improvements systematically, you don't know why you're getting improvements...There is a greater degree of inter-relationships among different elements [of the manufacturing process]--the same processes are used across different product lines. Communication (in a multinational company) is enhanced (and simplified) by the discipline over the organization. It does not require more overhead, rather less...For example, before [we] had planners in each operating group (with the product group, the fab, the test group, and the assembly operation). Now [we] have centralized the planning operation, and this has stabilized

[130]See <u>Electronic Buyers' News</u>, September 4, 1989, p. 44.

the operating plan...Overhead has been reduced by centralizing the functions--every group gets some part of the responsibility for balancing the overall plan...Job descriptions were expanded as part of the decentralizing the responsibilities."

- "We draft a product/process agreement or baseline agreement [with the customer] to achieve a state of awareness as to what is going on; we formally notify any change [to the customer]..."

- "Ten years ago...the issue was who could hire the best and the brightest product design engineer. An answer does not lie [today] in individual contribution to a company or relying on expertise in one area. Rather, the team/systems approach wins in today's IC house."

Application of SPC. Over the past five years, the single most important factor influencing overall quality levels in the U.S. industry has probably been the widespread adoption of SPC techniques. The insertion of SPC into mainstream practice required parallel changes in the organization. The changes included: (1) developing feedback processes to identify problems and their origins in the manufacturing process; and (2) increased effort for training at all levels, including the operator level, to understand and apply SPC concepts. The following comments were made on these two aspects of SPC in the survey interviews:

- "As we got into SPC and total quality concepts, we had to install a fast reaction system to deal with internal and external failures. With one plant testing 100 million devices every four weeks, you have to have feedback to fix the problem quickly--even within just one week you could

produce 100 million parts. Needed to create a team approach to quickly identify and fix the problem--both improvements and management aspects of problem solving."

- "SPC was not difficult to install, but it was a lengthy process requiring a lot of time, a great deal of training."
- "SPC is very important, thus [we] spend a lot on training individuals...[they] must be able to read and understand specifications...[thus] more is spent on training at all levels."

Changes in External Relationships

Two aspects of the external relationships have influenced quality-assurance practices in the U.S. semiconductor firms. The first is the influence of key end-markets, especially the changing influence of the military end-market. The second aspect is key elements of the relationship between equipment vendor and device producer.

(1) Changes in Key End-Markets Influence Over Quality Assurance Practices

Rotation of Leading QC End-Market. In Section C, the rotation of the leading QC end-market away from computer systems and the military end-markets toward the automotive and the Japanese markets was noted. In the early-1980s, at the same time the Japanese semiconductor industry demonstrated in the marketplace the quality levels that could be achieved, the U.S.

industry was losing its quality drivers. The military was pursuing outmoded techniques and fewer and fewer U.S. firms were able to stay the course in the costly computer systems houses market for DRAMs.[131] The following comments were received in the survey interviews on this point:

- "Five years ago [we] were very military-oriented and specifications were primarily what we went by. Now the use of SPC and the parallel cost improvement drive our philosophy...Currently, the requirements for the auto industry are driving the leading edge of the commercial industry base [for quality-assurance practices.]"

- "The military is very arbitrary and doesn't keep up with the technology very well; there is no exercising of the standard without good technical leadership.

- "The military community is not driving QC. The automotive industry is the single largest most aggressive QC driver followed by IBM..."

- "As one customer sets a new level of quality, it improves the situation across the entire customer base because you cannot maintain differential quality levels. There has to be one level of quality, and you have to operate to that level. In the case of [product], sold to Japan, it represented the largest market in world for this part. The demands of the Japanese customers drove improvements throughout [our] organization."

- "The military is behind the times--their audits are horrible, at best 10 percent do a good job..."

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[131] Only recently has the military begun to catch up with commercial practices in the area of quality assurance. For a lengthy statement on the "new" military views on quality assurance, see "A 'Living' Specification for the Future: QML," Electronic Buyers' News, July 31, 1989, insert at pp. T4-T24. DOD is currently seeking to establish a "quality czar" with the title Deputy Assistant Secretary for Total Quality Management, see Electronic Buyers' News, September 18, 1989, p. 1.

Audits to Qualification to Team Philosophy. Both Japanese and U.S. firms set up internal auditing procedures to monitor the progress and compliance of operating groups with quality-assurance practices and goals. (This is one of the missions of the quality-assurance staff in the reorganized QC organizations--see discussion above). But one area where there seems to be a difference in practice between Japanese and U.S. firms is in the use of audits by outside customers. There are two types of audits.[132] One type is by the military contractors. These audits are considered to be time consuming and of marginal benefit. The industry is trying to get them replaced by a process of third-party audits. In the commercial area, there is also some auditing that goes on. This is done to assure compliance to the customer's requirements for quality assurance.

The trend is now away from audits toward a wider use of qualification procedures. Once a firm is qualified, then the audits are dropped. There seems to be a trend toward a greater application of qualification procedures, just as in Japan, by a larger proportion of the customer base. Now there is a view toward achieving a partnership where the vendor and the customer work closely to build good products.

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[132]Audits are also conducted at the level of device producer and equipment/material vendor. For example, Intel audits each of its major suppliers once a year. (See Purchasing, August 17, 1989, p. 77.)

(2) Vendor Relationships

Shift Away From Technology Driven Approach to Quality Assurance. "During the early-1980s, more...emphasis was on buying the latest equipment. As the philosophy of quality has changed, [we] realized that existing equipment could be made more useful ([we] did not need new equipment) and other factors were more important."[133] This change reflects the overall shift in corporate philosophy toward quality assurance. First, it reflects the need to baseline manufacturing procedures--that is, establish a process, document it, and then drive incremental improvements. Stabilizing equipment on the line is part of this disciplined approach to yield enhancements. Second, it reflects the Japanese recognition that even equipment that is not state-of-the-art can be made to perform at higher and higher levels of performance and reliability with proper maintenance and attention to details. With elimination of attribute variability as the goal, a key outcome of application of SPC, focusing on thorough understanding of the existing tools becomes more important in the incremental philosophy of improvement.

Changes in the Procurement Process. An extensive set of changes is underway in the relationships between the leading-

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[133]Statement from our survey interviews.

edge QC semiconductor producers and materials/equipment vendors.[134] For example, the process is leading to a winnowing of suppliers down to the few who can meet the stringent quality-assurance requirements of the producers: "We have no commodities with more than three suppliers; more frequently we have only two suppliers. Sometimes we'll go with a single supplier, but if we do that, we make sure it's a supplier with dual factories or with dual tooling."[135] The net result of these changes is to move the relationships more into a mode of operation more characteristic of the type of coupling found between Japanese producers and their major vendors: a close working relationship keyed to meeting nonprice goals of the producer while accepting a more limited degree of price competition among different vendors. Among the key goals targeted to be attained from the qualification process is greater quality assurance in incoming materials. Additional comments on this point included:

- "There has been an increase in resources in the procurement process, and a larger portion of management dedicated to quality of incoming material. This is how procurement management is evaluated."

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[134]See Purchasing, "How to Push Your Everyday Supplier Into World Class Status," August 17, 1989, pp. 74-78, for discussion of the changes underway. It is outside the scope of this study to fully document the changes going on at this level.

[135]Purchasing, op. cit., p. 77.

- "[We have] a qualified vendor program...focusing downward on chemicals, configured materials, and masks...we keep nothing in stock, [our vendors] ship directly to the line."

SEMATECH. The only place where we could identify an organized push on material standards and equipment reliability is in SEMATECH. We mention this only in passing for completeness, but this aspect is decidedly different from the situation in Japan.

F. Summary and Future Directions

In this chapter we have documented the evolution of philosophies and operational approaches taken by the major Japanese and American semiconductor firms toward quality assurance. The changes in philosophies and practices were brought about, first of all, by the technical demands of ULSI-level technology described in Section C, and, for the American firms, the necessity to integrate Japanese views regarding quality strategies into their own corporate competitive strategies.

The Japanese semiconductor firms, as noted earlier, developed their general quality strategies and the implementing practices as part of the broad movement begun in Japan in the

1950s to improve quality. By the early-1980s, it was clear that the Japanese semiconductor firms had a focus on quality and an associated set of management practices that were neither as widely evident nor as intensively practiced in the United States.

However, especially in the past five years, a number of American semiconductor firms have sought to achieve parity with the Japanese in quality assurance as measured by PPM defects.[136] Part of the means to achieve parity was to adopt general QA concepts and methods from Japan and then tailor them to fit the American management context. Among this set of American firms that we call leading-edge practitioners of quality, it is difficult to discern major differences, relative to the Japanese, in general quality policies or even in key techniques used to implement their quality strategies.[137] Thus, when one compares QA strategies found at these U.S. leading-edge QA semiconductor firms to the QA strategies found at the major Japanese

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[136]In the auto industry, for example, the "Big-Three" U.S. automakers have reduced the defect gap with Japanese and European autos since 1980. In 1989, the U.S. had a lower defect rate than the Europeans and a rate lower than the 1986 Japanese rate. The Washington Post, January 3, 1990, p. C1.

[137]The leading-edge U.S. QA firms that adopt Japanese TQM concepts will tend to be larger U.S. firms, similar in size and scope of product offerings to the major Japanese semiconductor firms. However, since not all U.S. semiconductor firms have strategies based on manufacturing superiority such as most major Japanese semiconductor operations, they do not have, nor do they need to have, a set of quality-assurance practices that are identical to those found in Japanese semiconductor firms.

semiconductor firms, the differences are less stark, less black and white, than they would have been in the early-1980s.[138] The total quality management or control philosophy is now the level demanded of all leading-edge QC firms.

The differences between U.S. and Japanese semiconductor firms emerge in the detailed implementation of the TQM philosophy. Japanese companies have close couplings with outside organizations, greater emphasis on operator training, maintenance, and automation, and a focus on a selected set of measures of quality (for example, yield). American firms do not seem to have as coherent a view on putting resources in these areas--except, perhaps, in training. As American semiconductor firms move to effectively implement the Japanese philosophy of Total Quality Management, it will be essential to incorporate some elements of these micro aspects of the Japanese program. However, this will be increasingly difficult to accomplish because it will cut against organizational and behavioral practices highly ingrained in the West. Independent organizations in the West do not conform to the hierarchical

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[138]This view is consistent with Hewlett-Packard's (HP) assessment. "On one hand, Walter [quality director at HP] said he is encouraged by how many U.S. companies have improved the quality of their products, but he is still depressed to see so many that have not. He said the best U.S. chip-makers are now on par with the best of the Japanese, but, on average, quality in the United States still is not as high as in Japan." Electronic Buyers' News, September 4, 1989, p. 44.

model that is so dominant in Japan and that facilitates close coupling. Further, operators in Japan are part of a stable, highly educated work force; firms can invest in training knowing that there is limited mobility. Also important is the subjective valuative process in Japanese firms where all levels of the organization are aware of the different considerations impacting a decision and weigh preferences similarly. The result is an increasingly challenging set of conditions for American firms seeking to mimic the Japanese total approach to quality assurance.

There are several areas that NIST should consider for further evaluation regarding a comparison of Japanese and U.S. practices. First, given the growing emphasis in the semiconductor industry on competing on the basis of design (with short turn-around times) and service and support functions, it would be worthwhile to focus a study on how the two industries handle quality-assurance practices for this dimension of their business strategy. This issue is important because of the belief that American firms can excel in this area relative to their Japanese competitors. If correct, and if the PPM gap has indeed been closed, it suggests that American firms could gain competitive strength relative to Japanese firms in the future.

Second, it would be useful to NIST, as we suggested in the introduction, to use this paper as the means for driving a dialogue with U.S. semiconductor executives to increase their awareness of the areas where Japanese firms seem to be pursuing different approaches to quality. This process could be accomplished as part of a general NIST effort to gain greater visibility for its efforts to support quality-assurance efforts in the U.S. semiconductor industry. Third, it would also be useful to interview Japanese executives on quality-assurance issues to parallel the interview process conducted in the U.S.

Appendices

Appendix A

General Overview of Optical Fiber Industry

Appendix A

General Overview of Optical Fiber Industry[1]

I. Introduction

Fiberoptic technology permits the transmission of information by light pulses. There are three advantages to this technology compared to microelectronics technology, which uses copper wiring:

(1) more information can be transmitted in the same space;

(2) information can be transmitted at a lower cost; and

(3) the integrity, security, and quality of the transmitted information is greater.

Fiberoptic technology, or more generally photonics technology, is most widely applied in the area of telecommunications. However, the technology's importance in information processing, optical storage and display, and optical sensors will become more widely recognized as these application areas mature and become commercialized.

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[1]This appendix draws heavily from "U.S. Global Competitiveness: Optical Fibers, Technology and Equipment," U.S. International Trade Commission, January 1988 (hereafter, ITC 1988) and from "A Competitive Assessment (Update) of the U.S. Fiber Optics Industry," International Trade Administration, June 1988 (hereafter, ITA 1988).

Two supporting technologies are involved in a fiberoptics system. In communications, for example:

(1) Optoelectronics involves all activities related to the generation, manipulation, and detection of light signals. It provides the necessary transition between microelectronics and photonics.

(2) Optical fibers are used to guide the light signals.

The six major components of a fiberoptics system are:[2]

(1) Transmitters such as light-emitting diodes (LEDs) or diode lasers send the transformed electrical signal. While both are applicable as light sources, LEDs are less powerful and they operate at slower speeds. Accordingly, they are best suited for short-haul, low-information transmissions. Thus, LEDs are used primarily with multi-mode fibers (see below).

(2) Multiplexers split light signal wavelengths to allow for multiple frequency transmissions (often called light source transducers).

(3) Optical Fiber/Cable thin strands of doped-silica glass with silica or plastic; more than 400 fibers can be contained in one optical fiber cable.

(4) Connectors/Splicers join optical fiber segments together.

(5) Repeaters regenerate attenuated light pulses. They create electrical signal from the light pulse, amplify it, reconvert the electrical signal back into a light pulse and re-transmit.

(6) Receivers convert light pulses into electrical current (often called light detector transducers or photodiodes).

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[2]See ITA 1988, pp. 3-10.

In 1988, over 800 companies were involved in the production of at least one component of a fiberoptic system. The major U.S. companies producing these various components are listed in Table A.1. AT&T is the only one of these companies producing all of the components of a fiberoptic system.

The market for fiberoptic technology is growing. Table A.2 shows estimates of the size of the world market from 1986 to 1988, with projections to the Year 2000. It is projected that U.S. manufacturers' share of the world market will begin to increase in 1990 as domestic home-to-office communication networks increase. However, discussions with industry representatives suggest that the ITA forecast world market shares are too low.

The focus of this study is the optical fiber component of a fiberoptics system.

Table A.1

Major Fiberoptic Companies Producing in the United States

Optical Fiber:	Corning Glass Works* AT&T* Spectran Alcatel Sumitomo Electric**
Fiber Optic Cable:	Siecor* AT&T* Alcatel General Cable Belden Pirelli Sumitomo Electric** Simplex
Connectors:	AT&T Dorran/3M AMP Amphenol OFTI ITT-Cannon GTE NEC
Transmission Equipment:	AT&T* Rockwell* NEC America Telco Systems Fujitsu Stromberg Carlson GTE Harris
Splicing Equipment:	GTE AT&T 3M AMP Siecor Ericsson

Table A.1, continued

Major Fiberoptic Companies Producing in the United States

Multiplexers:	Fibronics*
	Gould
	GTE
	Artel
	Canoga-Perkins
	Versitron
	Phalo
	Astrocom

Notes: * denotes a dominant U.S. market share.

** As of February 1989, Sumitomo Electric Corporation, a subsidiary of Sumitomo Electric Industry of Japan, is only producing cable. The production of optical fiber is now done by LITESPEC, Inc., a joint venture between Sumitomo Electric Industry and AT&T.

Source: ITA 1988, p. 11.

Table A.2

Size of the U.S. and World Optical Fiber Markets
($ Millions)

Year	U.S.	World	U.S. Share of World Market
1986	$ 829	$ 1528	54.2%
1987	962	2073	46.4
1988	1063	2535	41.9
1989	1138	3190	35.6
1990	1440	3779	38.1
1995e	3255	7225	45.0
2000e	4611	10835	42.5

Source: ITA 1988, p. 22.

II. Characteristics of Optical Fiber

"Optical fibers used for voice, video, and data communications are hair-thin strands of glass or plastic which are usually combined in cables for transmitting information in the form of light pulses from one point to another."[3] There are three dimensions by which an optical fiber can be classified: mode, wavelength, and cladding.

Single-mode fibers permit only one mode or path for a light pulse. The advantage of this construction is that light pulses travel in sequence, and as a result, signals arrive with little or no distortion. Generally, single-mode fibers are used in long-haul networks. Repeaters are required about every 35 to 40 kilometers.

Multi-mode fibers have a larger core and thus allow for multiple-sequenced impulses and greater information capacity (bandwidth). Multi-mode fibers are primarily used for short- and medium-hauls, and in local area networks owing to the reduced possibility of signal distortion over short distances. Step index multi-mode fibers have the larger core and are used for

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[3]ITC 1988, p. 2-1.

short-haul transmissions; grade index multi-mode fibers have a smaller core and are thus used for medium-haul applications.

The transmission characteristics of fiber are classified in terms of a few usable wavelengths or "windows:" "first window" (850 nanometers),[4] "second window" (1300 nm) and "third window" (1550 nm). There is a tradeoff between wavelength and attenuation. With longer wavelength and bandwidth, attenuation of light pulses decreases and so does the need for repeaters.

Surrounding the core (inner layer) of fiber is a cladding (outer layer). Various characteristics of cladding relate to repeater spacing requirements.

III. Structure of the Optical Fiber Industry

A. U.S. Manufactures of Fiber

There are three product lines produced by optical fiber manufacturers: glass fiber for voice, data, and video transmission; glass fiber for nondata transmissions; and plastic fiber for both data and nondata uses. Corning, AT&T and Alcatel, are the three major U.S. producers of optical fiber, accounting

[4]A nanometer (nm) is one-billionth of a meter.

for over 90 percent of domestic sales by U.S. producers. The remaining 10 percent of the domestic market is served by smaller manufacturers who produce fiber as only one part of their final integrated product.

Table A.3 shows the estimated market shares in the U.S. optical fiber market of these four producers along with their 1986 production capacity (most recent data). Corning and AT&T had over 80 percent of this market during the 1983-1986 period (lasted published data), with Corning having the larger share. Industry personnel expect this distribution to remain fairly stable over the next five years with Alcatel gaining at the expense of the dominant two.

The production capacity of the U.S. industry increased over 50 percent from 1984 to 1985, and over 100 percent from 1985 to 1986. In 1986, Corning dominated the U.S. market in terms of production capacity accounting for over 50 percent of all domestic capacity. Industry officials expect that the inter-firm distribution of capacity will remain relatively stable through 1990, with each producer increasing their capacity by an average of 25 percent (over their 1986 levels). However, a significant portion of this capacity is not being used and is not expected to be used by the end of 1990. The U.S. optical fiber industry had only a 59 percent capacity utilization rate in 1986,

Table A.3

Major U.S. Manufacturers of Optical Fiber

Manufacturer	U.S. Market Share 1983-86	1986 Capacity (fiber/km)
Corning	} over 80%	1,700,000
AT&T		1,000,000
Alcatel*	8 - 10%	160,000
Spectran	2%	100,000
TOTAL		2,960,000

Note: *Alcatel was formally ITT-Valtec.

Source: ITC 1988, pp. 6-1, 6-4.

compared to an 80 percent rate for U.S. manufacturing industries as a whole. Industry experts expect the utilization rate to increase to near 70 percent by the end of 1990.

The value of domestic shipments of U.S. optical fiber was $268 million in 1987, up $2 million from 1986. To place the size of this industry in perspective, Kessler Marketing Intelligence estimates the worldwide fiberoptic market (which includes all six of the components listed above) to be just over $3 billion.

B. International Manufacturers of Fiber

Many of the producers of optical fiber outside of the United States are listed in Table A.4. Also shown in the table are the companies' estimated capacity (fiber/kilometer) and their relationship to U.S. firms (when known).

Industry experts estimate that the U.S. share of the world market is now between 45 percent and 50 percent.

Table A.4

Major International Producers of Optical Fiber, 1986

Country and Company	Technical Relationship	Estimated Capacity (km/yr)
United Kingdom		
Optical Fibres	Corning joint venture	250,000
STC	none	20,000
GEC	none	20,000
Pirelli General	none	25,000
France		
CLTO (CGE)	Corning licensee	25,000
Fiber Optiques Industries	Corning joint venture	55,000
West Germany		
AEG	none	10,000
Standard Electric Lorenz	none	15,000
Philips Kommunication Industry	none	5,000
Siecor GmbH	Corning joint venture	80,000 (1987)
Wacker/Sumitomo	none	100,000 (1987)
Italy		
Fib Ottiche Sud	Corning joint venture with Pirelli	75,000
Netherlands		
Philips	Corning licensee	60,000
Denmark		
NKT	AT&T licensee	20,000
Sweden		
L.M. Ericsson	none	15,000
Finland		
Nokia	none	5,000
Switzerland		
Cabloptic	none	4,000
Canada		
Northern Telecom	Corning licensee	N/A

Table A.4, continued

Major International Producers of Optical Fiber, 1986

Country and Company	Technical Relationship	Estimated Capacity (km/yr)
Japan		
Sumitomo	N/A	N/A
Furukawa	N/A	N/A
Fujikura	N/A	N/A
Hitachi	N/A	N/A
Dianichi Nippon	N/A	N/A
Showa Cable	N/A	N/A
Korea		
Samsung Semiconductor and Telecommunications*	ITT licensee	N/A
Daewoo Telecom Company Ltd.*	Northern Telecom licensee	N/A
Goldstar Fiber Optics Co. Ltd.	AT&T joint venture	40,000
Taihan Electric Wire Co. Ltd.	Sumitomo licensee	48,000
Australia		
Olex	Sumitomo licensee	N/A
Optical Waveguide Pty. Ltd.	Corning joint venture	N/A
New Zealand		
Austral Standard Cables Pty. Ltd.	N/A	N/A

Note: * denotes producers of both fiber and cable. There are no producers of cable in Hong King, Taiwan, or China.

Source: ITC 1988, p. 10-6 ff. and discussions with industry representatives.

IV. Optical Fiber Production Technology

A. Production Methods

Optical fiber is made in three distinct stages.[5] Stage 1 involves refining glass to produce rods of multi-component glass using one of several conventional melting techniques. State 2 involves the use of one of four vapor deposition techniques to produce silica-rich glass--preforms--from the multi-component rods. Lastly, Stage 3 involves the drawing of the preform into fiber.

All four of the vapor deposition techniques used today are variants of the basic technology developed by Corning in 1972.[6] Corning's outside vapor deposition (OVD) process, or outside vapor phase oxidation (OVPO) process, consists of building layers of soot on the outside of the core rod or mandrel. The layering occurs while the rod rotates over the flame--flame hydrolysis. Bell Laboratories modified Corning's preform process. In their inside or modified chemical vapor deposition (MCVD) process, gas vapor goes through a heated silica tube and layers of soot accumulate on its inside. The Japanese use a vapor axial

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[5] ITC 1988, p. 3-7 and Senior, John M. Senior, <u>Optical Fiber Communications: Principles and Practice</u> (Prentice-Hall, Inglewood Cliffs, NJ), 1985.

[6] See Chaffee, C. David, <u>The Rewiring of America: The Fiber Optics Revolution</u> (Academic Press, Orlando), 1988.

deposition (VAD) process. Using flame hydrolysis, silica soot is deposited at the bottom of a gathering bar. The rotating preform is then pulled upward. Philips (Dutch) developed the plasma-activated chemical vapor deposition (PCVD) technique. It is a variation of the AT&T MCVD process, but faster.

After the fiber is drawn through a furnace, in Stage 3, the fiber passes through a fiber diameter gauge and is then coated with either epoxy or plastic (buffer). Ultraviolet light is used to cure the coating before winding.

B. Emerging Trends in Production Technology

The Japanese and Dutch believe that future cost reductions and quality improvements will come from the integration of the preform and drawing stages into a single, continuous production process:

> "Japanese and Dutch industry officials and technologists are convinced that their...processes...lend themselves well to future continuous process manufacturing systems that will combine the separate steps...and will result in drastically reduced [production] costs."[7]

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[7]ITC 1988, p. 3-7.

U.S. government officials discount the importance of continuous manufacturing, and "they do not believe developments in that area will have an impact one way or the other on future global competitiveness in optical fibers."[8] U.S. industry experts agree.

V. Technological Trends Affecting the Optical Fiber Industry

There are two technological issues that are likely to affect the optical fiber industry. The first relates to Corning's patented technologies and the second relates to new generations of fibers and related equipment.

It is likely that Corning will continue to dominate the world market due to its technological leadership in production methods. There is, however, debate about the economic and competitive impact of the expiration of Corning's patents. Some contend that when current patents expire within the next decade, Corning will likely introduce new technological methods in order to maintain their technological lead.

Current optical fiber technology allows for the spacing of repeaters at about 50 km. Research on new generations of fiber

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[8] ITC 1988, p. 3-7.

material (flouride fibers) may increase the distance between repeaters by a factor of possibly 100. If so, transmission costs will fall dramatically and optical fibers will become more widely used. Also, new markets will develop in nontelecommunication areas once these fluoride fibers are commercialized. Better splicing techniques will similarly increase the world demand for optical fibers and fiberoptic technology. Fusion splicing is expected to improve transmission quality by reducing signal attenuation.[9]

[9]The use of optical fiber for telecommunications has increased steadily in recent years. Whereas only 10 percent of total telecommunication route miles were optical fiber in 1984, over 40 percent will be optical fiber by 1990. This increase will come at the expense of a decrease in the use of microwave, copper wire, and satellite technologies.

Appendix B

Survey of Investments in Quality in the Optical Fiber Industry

SURVEY OF INVESTMENTS IN QUALITY IN THE OPTICAL FIBER INDUSTRY

Conducted for the National Institute of Standards and Technology

by

Quick, Finan & Associates

Please return completed responses no later than August 31, 1989, to:

Laura Bauer
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Suite 200
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Washington, DC 20036
Telefax: (202) 296-0085
Telephone: (202) 223-4044

Please indicate below your firm's name and an individual from within your firm whom we may contact in case we have questions regarding your responses.

FIRM NAME : ______________________

NAME : ______________________

TITLE : ______________________

ADDRESS : ______________________

TELEPHONE : ______________________

TELEFAX : ______________________

Please answer all questions as accurately as you can. If you do not have the precise information requested, your educated guess is better than a blank. (Please indicate such approximations with an asterisk (*).)

Quality can be defined in terms of meeting certain objectives for performance levels and performance stability, reliability, longevity, and manufacturability. One simple definition is conformance to specifications and/or fitness for use.

Question 1
Definition of Quality

Question 1A. Does your firm's current definition of quality generally conform to the definition stated above? (Please check one.)

Yes _____ No _____

Question 1B. If you answered "No" to Question 1A, please explain how your firm's view of quality differs from the above definition.

____

____

____

____

Question 1C. Has your definition of quality changed within the past ten years? (Please check one.)

Yes _____ No _____

If so, how?

____

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____

____

PLEASE ANSWER THE REMAINING QUESTIONS USING YOUR FIRM'S CURRENT DEFINITION OF QUALITY

Question 2
Quality-Related Expenditures as a Percentage of Your Firm's Budget Categories and Total Budget

Question 2A. What is the percentage of your firm's total budget allocated toward achieving quality in each of the following time periods?

	Average During 1980-85	Current
Percentage of Total Budget Allocated Toward Achieving Quality	________	________

Please divide your firm's total annual budget or outlays into the following four categories: operations, capital investments, research and development (R&D), and overhead. We are interested in the relative amounts in each type of budget category that are allocated toward achieving quality. In addition we would like to know how the total budget allocated toward achieving quality has shifted among these categories over time. Quality-related outlays in each category should conform to the following guidelines:

- In the **Operations Budget**, quality-related expenditures include cost of engineering and technical support personnel responsible for yield improvement and sustaining processes. Outlays related to operator/technician training and certification are also included, with the exception of safety-related outlays. Outlays related to maintenance and repair should be excluded.

- In the **Capital Investments Budget**, quality-related expenditures include outlays that tighten tolerances and result in discernable enhancements or improvements in products or processes. Capital investments that only add volume should be excluded.

- In the **R&D Budget**, include expenditures related to manufacturability and new product design costs related to aggressive product line development and improvement. Costs related to new processes and adding or broadening product lines should be excluded. Also excluded are administrative overhead and application engineering.

- In the **Overhead Budget**, quality-related expenditures include direct outlays for quality staff and training costs associated with quality objectives not included in your operations budget. Safety-related outlays should be excluded in the overhead budget or the operations budget. Outlays related to general administration, accounting, credit and sales should be excluded.

Question 2B. What percentage of each of the following budget categories is quality related, as defined above?

	Percentage of Budget Category Allocated Toward Achieving Quality	
Budget Category	Average During 1980-85	Current
Operations Budget	______	______
Capital Investments Budget	______	______
R&D Budget	______	______
Overhead Budget	______	______

Question 2C. Some companies report that a decade ago total dollar expenditures related to quality were primarily in overhead for inspection and detection, but today the trend is toward spending more dollars on prevention in operations, R&D, and capital budgets. Has a similar shift taken place in your company? (Please check one.)

Yes ____ No ____

If so, please describe.

____

____

____

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Question 3
Estimated Distribution of Outlays of Total Quality Expenditures by Functional Category

Many firms also divide their total budget allocated toward achieving quality into the following five functional categories:

Expenditures related to acquiring, developing or improving technology, including:

> **Product technology:** (self-explanatory.)
>
> **Process technology:** (self-explanatory.)

Nontechnology-related expenditures for:

> Control: includes operations such as incoming-materials inspection, in-process monitoring, completed-product inspection/testing and statistical quality control.
>
> Improvement: involves procedural audits, analysis of process data; development of modifications to inspection procedures, process techniques, statistical quality control and quality awareness and training programs.
>
> Management: defines and monitors a quality system, including management reporting, engineering-support functions and quality management (quality engineering and quality control).

Question 3A. Referring to your firm's total budget allocated toward achieving quality (see Question 2A), approximately what percentage is allocated to the following functional categories (as defined above)?

Expenditure Category	Average During 1980-85	Current
Product Technology	______	______
Process Technology	______	______
Control	______	______
Improvement	______	______
Management	______	______
TOTAL	100%	100%

Question 3B. Some companies report that in the last ten years, the proportion of quality-related expenditures in the nontechnology-related areas (that is, control, improvement, and management) has been growing. Has a similar trend taken place in your company? (Please check one.)

Yes ____ No ____

If possible, please elaborate.

____

____

____

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Question 4
Estimated Distribution of Outlays of Total Quality Expenditures by Objective

Referring to your firm's total budget allocated toward achieving quality (see Question 2A), approximately what percentage is allocated toward achieving the following objectives?

OBJECTIVE	Average During 1980-85	Current
Improving Product Performance	____	____
Reducing Attribute Variability	____	____
Increasing Product Reliability	____	____
Decreasing Need for Serviceability	____	____
Increasing Product Life	____	____
Improving Manufacturability (Includes improved materials and processes)	____	____
Other ____________	____	____
____________	____	____
TOTAL	100%	100%

Question 5
Assessment of Quality as a Strategic Tool

Please respond to (check one) the following statements relating to quality as a competitive tool in the optical fiber industry.

Strategy	Strongly Agree	Somewhat Agree	Somewhat Disagree	Strongly Disagree
Quality is increasingly achieved through product design rather than new production technology.	______	______	______	______
With respect to production, quality is increasingly achieved through distinctly new technology rather than modifying existing technology,				
for mature products.	______	______	______	______
for new products.	______	______	______	______
An important component of quality improvement is user feedback provided by marketing/sales personnel.	______	______	______	______
R&D provides important technical support to nontechnology, quality-related activities.	______	______	______	______
Quality activities are guided primarily by what competing firms are doing with their product/ process strategies.	______	______	______	______
Improving product and process quality is a strategic option for GAINING market share.	______	______	______	______
Quality is an essential element of our cost reduction strategies.	______	______	______	______
Service quality is now the key way for a vendor to be differentiated from other vendors (service quality includes time to delivery, technical support, etc.).	______	______	______	______
On average, U.S. firms (other than yours) are willing to sacrifice some quality in order to introduce a product earlier than are Japanese firms.	______	______	______	______

Question 6
Barrier to Quality Improvement

In your judgment, what single factor is currently the greatest barrier to improving quality in optical fibers? Was this a significant barrier ten years ago? Three years ago?

____

____

____

Question 7
Measurement Expenditures

NIST has a particular concern for measurement-related expenditures, especially those related to quality. Measurement expenditures are those that yield information on certain attributes such as attenuation, dispersion, energy, area, and frequency via direct, indirect, comparison, and interpolation/extrapolation approaches.

Question 7A. Referring to your firm's current total budget allocated toward achieving quality (see Question 2A), approximately what percentage is devoted toward **measurement?** ________%

Question 7B. Where in the optical fibers business are measurement technology and expenditures most important in terms of your firm's overall competitive position? Please indicate the importance of measurement technology and expenditures to quality-related activity in your company by assigning a ranking (1 to 6, with no ties) to each stage in the manufacturing and marketing processes. (A rank of 1 indicates that measurement is more important in that manufacturing stage than in any of the others; a rank of 6 indicates measurement in that stage is least important.)

Stage of Production	Average During 1980-85	Current
Product Design	______	______
Input Purchases	______	______
Preform Fabrication	______	______
Drawing	______	______
Coating	______	______
Winding/Packaging	______	______

Question 7C. Please rank the following sources of measurement technology used to achieve quality. Please rank from 1 to 11 with 1 being the most important and 11 being the least important, and no ties. Please DO NOT rank those sources not familiar to you. Please mark those sources not familiar to you with "*."

	Relative Rank (No ties permitted)	
	Average During 1980-85	Current
External:		
Trade Associations (e.g., EIA, etc.)	______	______
Standards Bodies (e.g., ANSI, ASTM)	______	______
NIST (formerly NBS)	______	______
Other Federal Laboratories (e.g., Defense, NASA)	______	______
Suppliers (e.g., materials, equipment, engineering services)	______	______
Customers	______	______
Universities	______	______
Internal:		
R&D	______	______
Operating Divisions	______	______
Other:		
________________	______	______
________________	______	______

Question 8
Utilization of NIST Information

We ask that someone from your company who is familiar with NIST and your company's involvement with NIST answer this question.

Question 8A. During the past three years, has your company obtained quality-related information from NIST?

Yes _____ No _____

Question 8B. If you answered "Yes" to Question 8A, how do you rate this information on a five-point scale between 5 = Very Important and 1 = Not Important? ______

Question 8C. Based on your company's experience in utilizing NIST research and related services, how would you rate the following areas of NIST's activity with respect to **potential for improvement**? Please use the five-point scale described in Question 8B.

	Relative Importance
Joint Planning with Industry	_______
R&D Project Selection	_______
Scope of Measurement Research	_______
Depth of Measurement Research in Project Areas Selected	_______
Technology Transfer	_______
Standards Committee Participation	_______

THANK YOU FOR YOUR COOPERATION

Appendix C

General Overview of Semiconductor Industry

Appendix C

General Overview of Semiconductor Industry

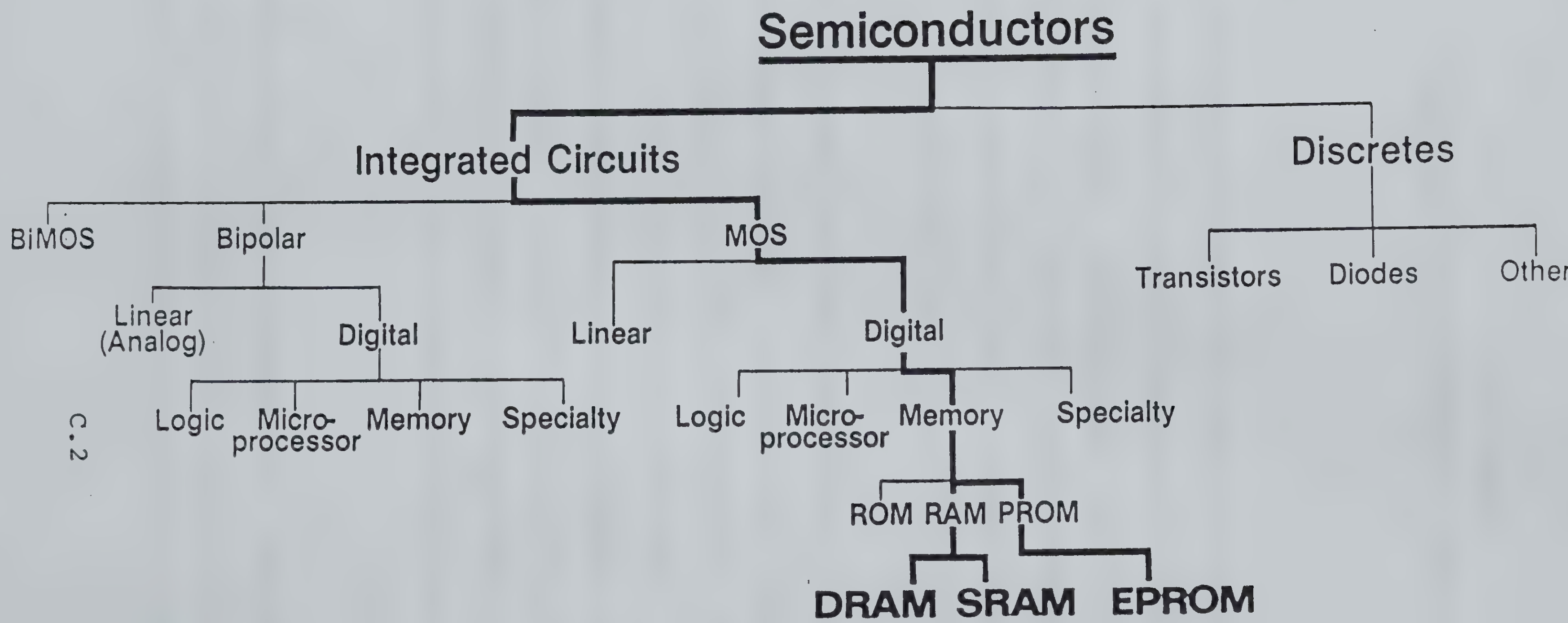
I. Introduction

Semiconductors are solid-state microelectronic devices made from materials that have intermediate electrical conductive characteristics--thus the name semiconductor. Semiconductor devices are either discrete circuit elements (i.e., transistors and diodes) or integrated circuits (ICs) with several circuit elements combined on one substrate. (See Figure 1.)

The value and use of semiconductor devices comes from their very small size and power requirements. Since the invention of the transistor in 1947, semiconductors have made their way into seemingly every part of consumer and industrial life. Semiconductors are now integral parts of automobiles, television sets, weapons systems and of course computers. Figure 2 shows the major categories of semiconductor consumption worldwide in 1989. Computers are the largest category using 40 percent of all 1989 semiconductor sales.

While the semiconductor was invented in the United States, the technology has now spread throughout the world. The top two semiconductor producers in 1989 were Japanese companies, holding

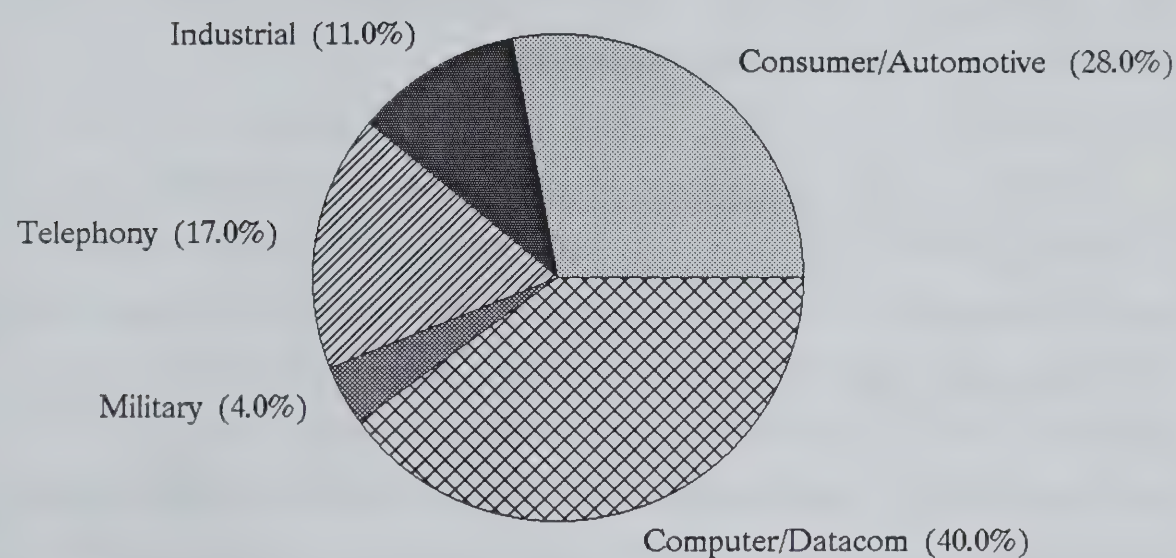
Figure 1


Semiconductors
Integrated Circuits
Discretes
BiMOS
Bipolar
MOS
Transistors
Diodes
Other
Linear (Analog)
Digital
Linear
Digital
Logic
Micro-processor
Memory
Specialty
Logic
Micro-processor
Memory
Specialty
ROM
RAM
PROM
DRAM
SRAM
EPROM

C.2

Figure 2

WORLDWIDE SEMICONDUCTOR SALES BY SECTOR, 1989



Source: Integrated Circuit Engineering, 1990, p. 1–7

over 17 percent of worldwide merchant sales. IBM (a captive producer) is the third largest producer worldwide. The largest European producer is Philips, which had a 2.7 percent market share in 1989. Samsung, a Korean producer jumped to a 2.5 percent share in 1989,[1] and they are expected to capture almost 4 percent of the world market by 1993.[2]

Figure 3 shows the value of worldwide semiconductor sales (including captives) since 1983 and forecasted values through 1994. Sales were $62 billion in 1989 and after levelling out in 1990 sales are expected to grow to $95 billion by 1994.[3] U.S. companies held 40 percent of the market share in 1989 (representing a 3 percent decline from the previous year) with $24.65 billion in total (captive and merchant) sales.[4] (See Figure 4.)

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[1]The Philips and Samsung market shares were calculated from information in Integrated Circuit Engineering Corporation, Status 1990: A Report on the Integrated Circuit Industry, Scottsdale, Arizona, 1990.

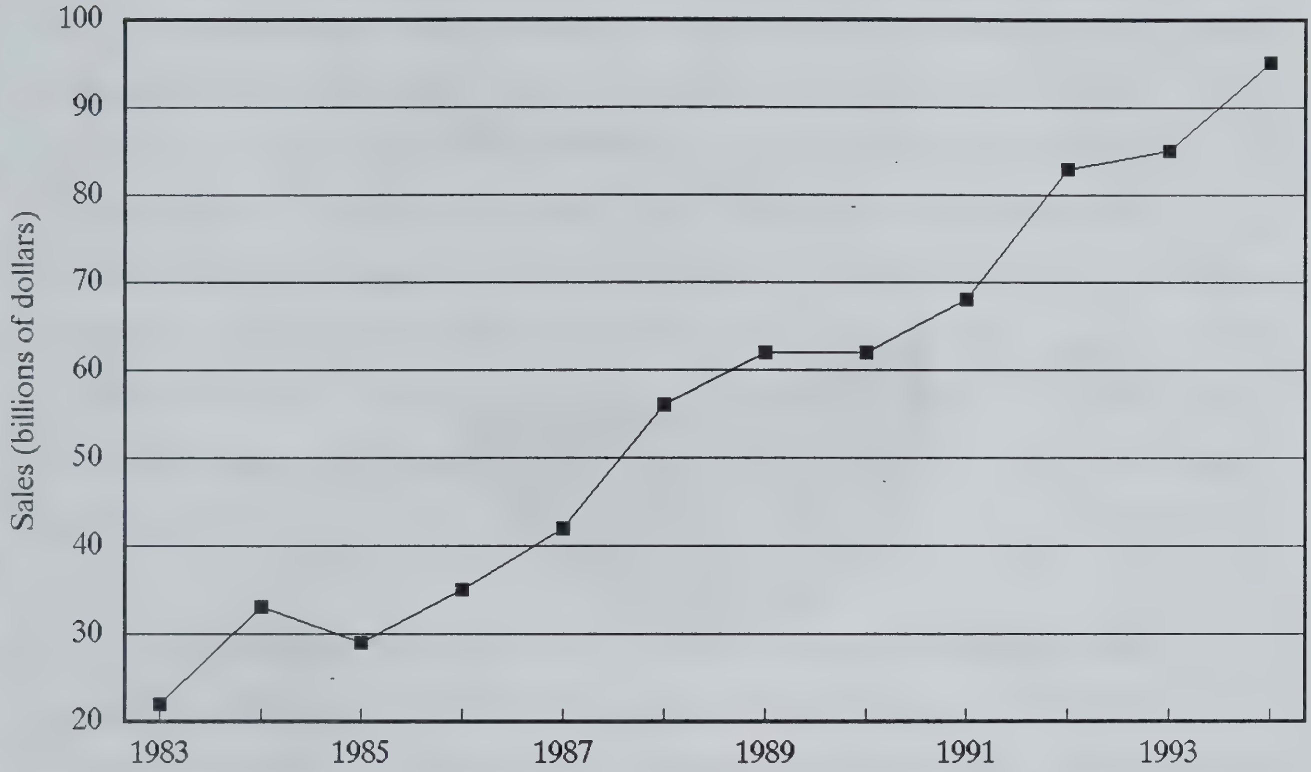
[2]Integrated Circuit Engineering Corporation (ICE), Mid-Term 1989 Status and Forecast of the IC Industry, 1989.

[3]ICE, 1990, p. 1-4.

[4]ICE, 1990, p. 1-9.

Figure 3

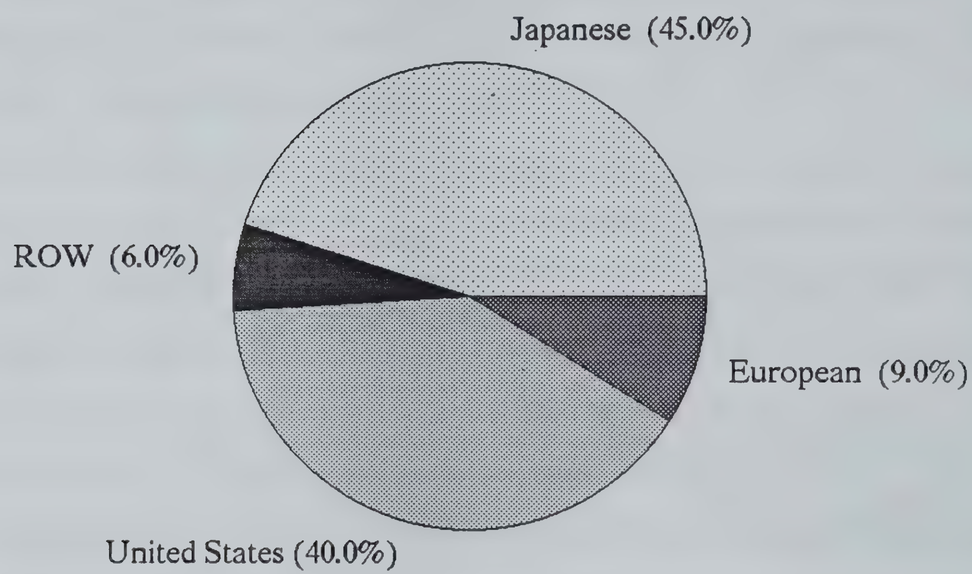
WORLDWIDE SEMICONDUCTOR SALES, 1983–1994



Source: Integrated Circuit Engineering, 1990, p. 1–4

Figure 4

WORLDWIDE SEMICONDUCTOR SALES BY COMPANIES, 1989 ($61.8B)



Source: Integrated Circuit Engineering, 1990, p. 1–9

II. Characteristics of Semiconductors

The original semiconductors were discrete devices that were composed of individual circuits that performed a specific function. The most basic device in this category is the transistor. Discrete devices most commonly used today are transistors, diodes and similar devices frequently utilized in stereos and heavy-equipment controlling mechanisms. Optoelectronic devices that either emit or respond to light are another form of discrete semiconductor, and they currently play an important role in telecommunications.

Integrated circuits, on the other hand, are much more complex devices typically composed of hundreds of thousands, or even millions, of transistors or other such devices that are then mounted onto a single chip. The production of ICs far outnumbers the production of discrete devices,[5] and consequently, the term semiconductor generally refers to ICs. Currently, the three main types of ICs produced are: digital memory, digital logic and linear circuits. Memory chips are used for storing information either temporarily or permanently. The main types of memory circuits are random-access memories (RAMs) (dynamic random access

[5]According to ICE, 1989 worldwide production of ICs equaled $52.3 billion while discrete devices equaled $9.5 billion.

memories (DRAMs) and static random access memories (SRAMS)), read only memories (ROMs), and programmable read only memories (PROMs). Logic chips are used to process instructions and data as demonstrated by microprocessors and their support chips. Application specific ICs (ASICs) represent logic chips that are produced for custom use and are "application specific." Linear ICs perform analog or continuous functions, often in the process of transforming digital outputs into analog such as in video screens or radio speakers.

III. Semiconductor Industry

In 1989 the U.S. semiconductor industry experienced the third consecutive year of expansion, with the value of product shipments 13 percent greater than in 1988. However, 1989 represents a dramatic slowdown in growth compared to the 33 percent growth in the previous year. The sluggish growth in the industry is expected to continue through 1990 because of slower growth in the overall economy and in the computer and telecommunications sectors. In addition, whereas prices for DRAMs remained firm in 1988, prices fell sharply in 1989 for many types of DRAM as supplies increased while more advanced 4-megabit DRAMs came into production.

Production of semiconductors in the United States is divided between merchant and captive production. Captive producers, such as IBM and Hewlett-Packard, manufacture semiconductors principally for internal use, whereas merchant manufacturers produce for market consumption. In 1989, merchant production by American companies equaled 76 percent of the total American production of semiconductors. The top three American merchant producers for 1989 were Motorola, Texas Instruments, and Intel.

The greatest challenge to the United States semiconductor industry is Japan, accounting for 45 percent of all semiconductor sales worldwide and for 75 percent of worldwide DRAM production in 1988.[6] Furthermore, six of the top 10 worldwide merchant manufacturers are Japanese,[7] and these companies alone account for 73 percent of Japanese production.

Europe is the third largest producer of semiconductors worldwide with a market share of 9 percent in 1989. However, the European industry is not very threatening to U.S. producers since the largest European IC producer, Philips, would not even rank among the top five American vendors. Furthermore, the opening of European borders in 1992 is seen as potentially positive to both

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[6]U.S. Department of Commerce, 1989, p. 30-3.

[7]NEC, Toshiba, Hitachi, Mitsubishi, Fujitsu and Matsushita.

American and Japanese firms that have already built up strong operations inside Europe.

Korea, whose semiconductor industry produced $2.4 billion in 1989, is also becoming a major participant in international markets and experienced a boom in production of 170 percent in 1988 and 63 percent in 1989. With increased potential emerging from a higher level of technology in Korea, companies such as Samsung, Goldstar and Hyundai will expand their sales in the 1990s substantially. Taiwan, a small producer currently with only a 0.5 percent worldwide market share, is expected to gain a 4 to 5 percent market share by the early 1990s.

U.S. semiconductor exports experienced a mild increase in 1989 with an overall increase of 10.3 percent; however, a 10.8 percent decline is predicted for 1990.[8] Much of the earlier stimulus for depended on a strong international demand for semiconductors as well as the devalued U.S. dollar. Both of these conditions deteriorated in 1989 and a further slowdown is predicted for 1990. Exports to Europe grew 45 percent in 1988, and that market remained strong for U.S. devices in 1989. Meanwhile, in 1989 exports to Japan increased an estimated 15 percent, yet, U.S.-Japanese trade in semiconductors remains

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[8] Department of Commerce, 1990, p. 19-2.

problematic and heavily influenced by the U.S.-Japan Semiconductor Trade Arrangement.[9]

U.S. imports increased 8.5 percent in 1989, which represents a significant decrease from the 43.3 percent jump in 1988.[10] Japan continues leading the way as the largest supplier of imports to the U.S. The trade imbalance with Japan alone accounted for 43 percent of the 1989 U.S. deficit in semiconductors. This deficit increased about 3.5 percent in 1989 to $3.0 billion,[11] and the outlook for 1990 is not much better with an expected deficit of nearly $3.3 billion.[12] This deficit reflects the difficulties of American firms in gaining access to the Japanese market as well as the heavy reliance on Japan for memory devices. Another contributing factor to the semiconductor trade deficit is the importation of semiconductors fabricated by American manufacturers overseas.

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[9]ICE, 1990, p. 1-28.

[10]Department of Commerce, 1990, p. 19-2.

[11]Department of Commerce, 1990, p. 19-2.

[12]Department of Commerce, 1990, p. 19-4.

IV. Semiconductor Production Technology

Originally ICs were fabricated by a process known as bipolar in which electricity is conducted by both positive and negative charges.[13] The alternative process, producing metal-oxide semiconductors (MOS), is unipolar (using positive or negative charges but not both).[14] MOS circuits can be more densely packed and have increased in speed to the point that MOS is generally the preferred process technology. Digital memory devices are most commonly MOS ICs.[15]

Within these two production processes are various sub-technologies that are specific applications of the two processes. While the balance of production is moving toward the MOS process, certain technologies within each process are gaining prominence. The technologies currently on the rise include two MOS techniques, CMOS and BiCMOS, as well as two bipolar techniques, ECL and GaAs.

---

[13] Office of Technology Assessment, International Competitiveness in Electronics, November 1983, p. 505. A more technical definition is that the current flow depends on the movement of majority and minority carriers (negatively charged electrons and holes that behave as if they were positively charged.)

[14] Technically defined, the MOS process is such that the current flow depends on the movement of majority carriers only (electrons or holes).

[15] OTA, 1983, p. 74.

The market for MOS-produced ICs is currently experiencing a transition from NMOS technology to CMOS and BiCMOS technology. Key factors in the rising popularity of CMOS technology are its design simplicity, speed and power characteristics, as well as the prospect of attaining bipolar speed performance as lithography techniques improve. BiCMOS technology offers both the high speed performance of ECL-type bipolar production and the high density/low power characteristics of CMOS. Forecasts expect these two techniques to account for 97 percent of all MOS production by 1994 or an amount equivalent to $58.2 billion,[16] and although the utilization of BiCMOS technology is expected to grow tremendously, its technical complexity will likely prevent its widespread usage before the mid-1990s.

Although bipolar technology will continue to decrease its market share into the 1990s, the nominal value of bipolar production should grow, albeit slowly. Whereas Japanese companies dominate the production of MOS, American companies hold the largest market share of bipolar production at 46 percent.[17] One advantage for the U.S. may come from the fact that the emphasis on this technique should help in the complex production of BiCMOS structures.

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[16]ICE, 1990, p. 5-3.

[17]ICE, 1990, p. 5-4.

The leading-edge technologies in bipolar production are ECL and GaAs production techniques. ECL technology is currently the most popular technique for high-speed circuit performance. GaAs-produced ICs are also gaining in popularity although their usage is currently inhibited by high processing and material costs. The market for GaAs ICs is predicted to grow from $130 million in 1988 to $950 million in 1994, with the principle consumer being the United States, which accounted for 80 percent of 1988 consumption. However, GaAs technology will most likely remain in limited use notwithstanding a breakthrough that would substantially lower production costs.

V. Further Reading on Semiconductors

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Appendix D

Survey of Investments in Quality in the Semiconductor Industry

SURVEY OF INVESTMENTS IN QUALITY IN THE SEMICONDUCTOR INDUSTRY

Conducted for the National Institute of Standards and Technology

by

Quick, Finan & Associates

Please return completed responses no later than September 15, 1989, to:

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Telephone: (202) 223-4044

Please indicate below your firm's name and an individual from within your firm whom we may contact in case we have questions regarding your responses.

FIRM NAME : ____________________

NAME : ____________________

TITLE : ____________________

ADDRESS : ____________________

TELEPHONE : ____________________

TELEFAX : ____________________

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____

____

____

____

Question 1C. Has your definition of quality changed within the past ten years? (Please check one.)

Yes _____ No _____

If so, how?

____

____

____

____

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- In the **Capital Investments Budget**, quality-related expenditures include outlays that tighten tolerances and result in discernable enhancements or improvements in products or processes. Capital investments that only add volume should be excluded.

- In the **R&D Budget**, include expenditures related to manufacturability and new product design costs related to aggressive product line development and improvement. Costs related to new processes and adding or broadening product lines should be excluded. Also excluded are administrative overhead and application engineering.

- In the **Overhead Budget**, quality-related expenditures include direct outlays for quality staff and training costs associated with quality objectives not included in your operations budget. Safety-related outlays should be excluded in the overhead budget or the operations budget. Outlays related to general administration, accounting, credit and sales should be excluded.

Question 2B. What percentage of each of the following budget categories is quality related, as defined above?

	Percentage of Budget Category Allocated Toward Achieving Quality	
Budget Category	Average During 1980-85	Current
Operations Budget	______	______
Capital Investments Budget	______	______
R&D Budget	______	______
Overhead Budget	______	______

Question 2C. Some companies report that a decade ago total dollar expenditures related to quality were primarily in overhead for inspection and detection, but today the trend is toward spending more dollars on prevention in operations, R&D, and capital budgets. Has a similar shift taken place in your company? (Please check one.)

Yes ____ No _____

If so, please describe.

____

____

____

____

____

Question 3
Estimated Distribution of Outlays of
Total Quality Expenditures by Functional Category

"Quality costs help to measure overall quality activities within a business, supplying cross-checks for measuring inputs against outputs. Inputs are the investments and expenditures in prevention and the supporting appraisal work; the resultant outputs are internal failures and external failures.

The four primary areas of cost breakdown needed to weigh inputs and outputs are (a more detailed breakdown can be found in the attached glossary):

1. Prevention: Costs associated with personnel engaged in designing, implementing and maintaining the quality system. The latter includes auditing the system.

2. Appraisal: Costs associated with measuring, evaluating or auditing products, components and purchased materials to assure conformance with quality standards and performance requirements.

3. Internal Failures: Costs associated with defective products, components and materials that fail to meet quality requirements and cause manufacturing losses.

4. External Failures: Costs generated by defective products being shipped to customers."[18]

Question 3A. Referring to your firm's TOTAL expenditures to achieve quality in Question 2A, approximately what percentage is allocated to each of the following primary areas of cost breakdown (as defined above)?

Expenditure Category	Average During 1970s	Average During 1980-85	Current
Prevention	______	______	______
Appraisal	______	______	______
Internal Failure	______	______	______
External Failure	______	______	______
TOTAL	100%	100%	100%

[18] Taken from Quality Costs--What & How, prepared by the Quality Cost-Cost Effectiveness Technical Committee of the American Society for Quality Control, Inc. Even though these areas of cost breakdown are based on ASQC definitions, costs of capital equipment should be included in each relevant category.

Question 3B. Some companies report that a decade ago, quality and defect-prevention-related expenditures were primarily in acquiring, developing, and improving technology rather than in nontechnology-related expenditure areas such as control, improvement, and management, where these concepts are defined as:

-- **Control:** includes operations such as incoming-materials inspection, in-process monitoring, completed-product inspection/testing and statistical quality control.

-- **Improvement:** procedural audits, analysis of process data; development of modifications to inspection procedures, process techniques, statistical quality control and quality awareness and training programs.

-- **Management:** defines and monitors a quality system, including management reporting, engineering-support functions and quality management (quality engineering and quality control).

Given these definitions, would you agree or disagree that the proportion of quality-related expenditures in the nontechnical areas has been growing. (Please check one)

Agree ____ Disagree ____

Please comment on conditions at your firm:

____

____

____

Question 4
Estimated Distribution of Outlays of Total Quality Expenditures by Objective

Referring to your firm's total budget allocated toward achieving quality (see Question 2A), approximately what percentage is allocated toward achieving the following objectives? [NOTE: You may feel more comfortable answering this question for a "representative" product, or for several products to provide a range, rather than give an average for all semiconductor product lines.]

OBJECTIVE	Average During 1980-85	Current
Improving Product Performance	______	______
Reducing Attribute Variability	______	______
Increasing Product Reliability	______	______
Reduced Cost of Test and Quality Assessment	______	______
Improving Manufacturability (Includes improved materials and processes)	______	______
If reporting for a representative product(s), please describe		
Other ______________________	______	______
______________________	______	______
TOTAL	100%	100%

Question 5
Assessment of Quality as a Strategic Tool

Please respond to (check one) the following statements relating to quality as a competitive tool in the semiconductor industry.

Strategy	Strongly Agree	Somewhat Agree	Somewhat Disagree	Strongly Disagree
Quality is increasingly achieved through product design rather than new production technology.	____	____	____	____
With respect to production, quality is increasingly achieved through distinctly new technology rather than modifying existing technology,				
for mature products.	____	____	____	____
for new products.	____	____	____	____
An important component of quality improvement is user feedback provided by marketing/sales personnel.	____	____	____	____
R&D provides important technical support to nontechnology, quality-related activities.	____	____	____	____
Quality activities are guided primarily by what competing firms are doing with their product/process strategies.	____	____	____	____
Improving product and process quality is a strategic option for GAINING market share.	____	____	____	____
Quality is an essential element of our cost reduction strategies.	____	____	____	____
Service quality is now the key way for a vendor to be differentiated from other vendors (service quality includes time to delivery, technical support, etc.).	____	____	____	____
On average, U.S. firms (other than yours) are willing to sacrifice some quality in order to introduce a product earlier than are Japanese firms.	____	____	____	____

Question 6
Barrier to Quality Improvement

In your judgment, what single factor is currently the greatest barrier to improving quality in semiconductors? Was this a significant barrier ten years ago? Three years ago?

____

____

____

Question 7
Measurement Expenditures

NIST has a particular concern for measurement-related expenditures, especially those related to quality. Measurement expenditures are those that yield information on certain attributes such as area, capacity, energy, and induction via direct, indirect, comparison, and interpolation/extrapolation approaches. For semiconductors, NIST has categorized its metrology work as follows: (1) Materials and Structures Metrology, (2) Critical Process Metrology, (3) Advanced Device Metrology, and (4) Manufacturing Metrology.

Question 7A. Referring to your firm's current total budget allocated toward achieving quality (see Question 2A), approximately what percentage is devoted toward **measurement?** ________%

Question 7B. Where in the semiconductor business are measurement technology and expenditures most important in terms of your firm's overall competitive position? Please indicate the importance of measurement technology and expenditures to quality-related activity in your company by assigning a ranking (1 to 10, with no ties) to each stage in the manufacturing and marketing processes. (A rank of 1 indicates that measurement is more important in that manufacturing stage than in any of the others; a rank of 10 indicates measurement in that stage is least important.)

	Life Cycle Stage			
	New Product Development and Production Ramp		Volume Production/ Mature Product	
Stage in Manufacturing/ Marketing Process	Pre-1986	Current	Pre-1986	Current
R & D	______	______	______	______
Product Design	______	______	______	______
Consumables Procurement (e.g.,Chemicals, Gases)	______	______	______	______
Materials Procurement (e.g., Silicon, Bonding Compound Packaging)	______	______	______	______
Equipment Procurement	______	______	______	______
Wafer Fabrication	______	______	______	______
Assembly	______	______	______	______
Test	______	______	______	______
Qualification as Vendor	______	______	______	______
Marketing of Final Product	______	______	______	______

Question 7C. Please rank the following sources of measurement technology used to achieve quality. Please rank from 1 to 11 with 1 being the most important and 11 being the least important, and no ties. Please DO NOT rank those sources not familiar to you. Please mark those sources not familiar to you with "*."

	Relative Rank (No ties permitted)	
	Average During 1980-85	Current
External:		
Trade Associations (e.g., SIA, SEMI, etc.)	_____	_____
Standards Bodies (e.g., ANSI, ASTM)	_____	_____
NIST (formerly NBS)	_____	_____
Other Federal Laboratories (e.g., Defense, DoE)	_____	_____
Suppliers (e.g., materials, equipment, engineering services)	_____	_____
Customers	_____	_____
SRC	_____	_____
SEMATECH	_____	_____
Universities	_____	_____
Internal:		
R&D	_____	_____
Operating Divisions	_____	_____
Other:		
_______________	_____	_____
_______________	_____	_____

Question 8
Utilization of NIST Information

We ask that someone from your company who is familiar with NIST and your company's involvement with NIST answer this question.

Question 8A. During the past three years, has your company obtained quality-related information from NIST?

Yes _____ No _____

Question 8B. If you answered "Yes" to Question 8A, how do you rate this information on a five-point scale between 5 = Very Important and 1 = Not Important? _____

Question 8C. Based on your company's experience in utilizing NIST research and related services, how would you rate the following areas of NIST's activity with respect to **potential for improvement**? Please use the five-point scale described in Question 8B.

	Relative Importance
Joint Planning with Industry	_______
R&D Project Selection	_______
Scope of Measurement Research	_______
Depth of Measurement Research in Project Areas Selected	_______
Technology Transfer	_______
Standards Committee Participation	_______

THANK YOU FOR YOUR COOPERATION

Appendix E

Survey of Investments in Quality in the Semiconductor Industry: The Role of Measurement

SURVEY OF INVESTMENTS IN QUALITY IN THE SEMICONDUCTOR INDUSTRY:
The Role of Measurement

Conducted for the National Institute of Standards and Technology

by

Quick, Finan & Associates

Please return completed responses no later than December 1, 1989, to:

William Finan
Quick, Finan & Associates
Suite 200
1133 - 21st Street, NW
Washington, DC 20036
Telefax: (202) 296-0085
Telephone: (202) 223-4044

Please indicate below your firm's name and an individual from within your firm whom we may contact in case we have questions regarding your responses.

FIRM NAME : ______________________________

NAME : ______________________________

TITLE : ______________________________

ADDRESS : ______________________________

TELEPHONE: ______________________________

TELEFAX : ______________________________

Please answer all questions as accurately as you can. If you do not have the precise information requested, your educated guess is better than a blank. (Please indicate such approximations with an asterisk (*).)

Quality can be defined in terms of meeting certain objectives for performance levels and performance stability, reliability, longevity, and manufacturability. One simple definition is conformance to specifications and/or fitness for use.

NIST has a particular concern for measurement-related expenditures, especially those related to quality. **Measurement** expenditures are those that yield information on certain attributes such as area, capacity, energy, and induction via direct, indirect, comparison, and interpolation/extrapolation approaches. For semiconductors, NIST has categorized its metrology work as follows: (1) Materials and Structures Metrology, (2) Critical Process Metrology, (3) Advanced Device Metrology, and (4) Manufacturing Metrology.

Question 1. Please rank the relative importance of the following sources of measurement technology used to achieve quality. Please rank from 1 to 11 with 1 being the most important and 11 being the least important, and no ties. Please DO NOT rank those sources not familiar to you. Please mark those sources not familiar to you with "*."

	Pre-1986	Current
External:		
Trade Associations (e.g., SIA, SEMI, etc.)	_______	_______
Standards Bodies (e.g., ANSI, ASTM)	_______	_______
NIST (formerly NBS)	_______	_______
Other Federal Laboratories (e.g., Defense, DoE)	_______	_______
Suppliers (e.g., materials, equipment, engineering services)	_______	_______
Customers	_______	_______
SRC	_______	_______
SEMATECH	_______	_______
Universities	_______	_______
Internal:		
R&D	_______	_______
Operating Divisions	_______	_______
Other:		
_______________	_______	_______
_______________	_______	_______

Question 2. During the past three years, has your company obtained quality-related information from NIST?

Yes ____ No _____

Question 3. If you answered "Yes" to Question 2, how do you rate this information on a five-point scale between 5 = Very Important and 1 = Not Important? ______

Question 4. Based on your company's experience in utilizing NIST research and related services, how would you rate the following areas of NIST's activity with respect to **potential for improvement**? Please use the five-point scale described in Question 3.

	Relative Importance
Joint Planning with Industry	_______
R&D Project Selection	_______
Scope of Measurement Research	_______
Depth of Measurement Research in Project Areas Selected	_______
Technology Transfer	_______
Standards Committee Participation	_______

Question 5. It is important for NIST to know where in the semiconductor business measurement technology and expenditures are most important in terms of your firm's overall competitive position. Please indicate your professional opinion of the importance of measurement technology and expenditures to quality-related activity in your company for both new and mature products.

Question 5A. Please assign a ranking (1 to 10, no ties) **for new products**. A rank of 1 indicates that measurement is more important in that manufacturing stage than in any of the others; a rank of 10 indicates measurement in that stage is least important.

	New Product	
Stage in Manufacturing/Marketing Process	Pre-1986	Current
R & D (New Process Development)	______	______
Product Design	______	______
Consumables Procurement (e.g., Chemicals, Gases)	______	______
Materials Procurement (e.g., Silicon Wafers, Bonding Compound, Packaging)	______	______
Equipment Procurement	______	______
Wafer Fabrication	______	______
Assembly	______	______
Test	______	______
Qualification as Vendor	______	______
Marketing of Final Product	______	______

Question 5B. Please assign a ranking (1 to 10, no ties) **for mature products**. A rank of 1 indicates that measurement is more important in that manufacturing stage than in any of the others; a rank of 10 indicates measurement in that stage is least important.

Stage in Manufacturing/Marketing Process	Mature Product: Pre-1986	Mature Product: Current
R & D (New Process Development)	______	______
Product Design	______	______
Consumables Procurement (e.g., Chemicals, Gases)	______	______
Materials Procurement (e.g., Silicon Wafers, Bonding Compound, Packaging)	______	______
Equipment Procurement	______	______
Wafer Fabrication	______	______
Assembly	______	______
Test	______	______
Qualification as Vendor	______	______
Marketing of Final Product	______	______

Question 6. Do you have any additional observations, comments or suggestions regarding NIST activities and the role of measurement in the U.S. semiconductor industry's drive to sustain and improve quality and global competitiveness?

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THANK YOU FOR YOUR COOPERATION

Appendix F

Glossary of Surveys of Investments in Quality in the Semiconductor Industry

Appendix F

Glossary of Surveys of Investments in Quality in the Semiconductor Industry

(1) Budget Categories

- In the **Operations Budget**, quality-related expenditures include cost of engineering and technical support personnel responsible for yield improvement and sustaining processes. Outlays related to operator/technician training and certification are also included, with the exception of safety-related outlays. Outlays related to maintenance and repair should be excluded.

- In the **Capital Investments Budget**, quality-related expenditures include outlays that tighten tolerances and result in discernable enhancements or improvements in products or processes. Capital investments that only add volume should be excluded.

- In the **R&D Budget**, include expenditures related to manufacturability and new product design costs related to aggressive product line development and improvement. Costs related to new processes and adding or broadening product lines should be excluded. Also excluded are administrative overhead and application engineering.

- In the **Overhead Budget**, quality-related expenditures include direct outlays for quality staff and training costs associated with quality objectives not included in your operations budget. Safety-related outlays should be excluded from the overhead budget or the operations budget. Outlays related to general administration, accounting, credit and sales should be excluded.

(2) QA Cost Categories[1]

"Quality costs help to measure overall quality activities within a business, supplying cross-checks for measuring inputs against outputs. Inputs are the investments and expenditures in prevention and the supporting appraisal work; the resultant outputs are internal failures and external failures.

- **Prevention:** Costs associated with personnel engaged in designing, implementing and maintaining the quality system. The latter includes auditing the system.

  Quality Control Engineering
  Process Control Engineering
  Design and Development of Quality Measurement and Control Equipment
  Quality Planning by Functions other than Quality Control
  Quality Training
  Other Prevention Expenses

- **Appraisal:** Costs associated with measuring, evaluating or auditing products, components and purchased materials to assure conformance with quality standards and performance requirements.

  Receiving or Incoming Test and Inspection
  Laboratory Acceptance Testing
  Inspection and Test
  Checking Labor
  Set-up for Inspection and Test
  Inspection and Test Materials
  Product Quality Audits
  Outside Endorsements or Approval
  Maintenance and Calibration of Test and Inspection Equipment used in Quality Control
  Review of Test and Inspection Data
  Field Performance Testing
  Internal Testing and Release
  Evaluation of Field Stock and Spare Parts
  Calibration and Maintenance of Production Equipment used to Evaluate Quality

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[1]Taken from Quality Costs--What & How, prepared by the Quality Cost-Cost Effectiveness Technical Committee of the American Society for Quality Control, Inc.

Data-Processing Inspection and Test Reports
Special Product Evaluations
Test and Inspection Materials

- **Internal Failures:** Costs associated with defective products, components and materials that fail to meet quality requirements and cause manufacturing losses.

  Scrap
  Rework and Repair
  Troubleshooting or Failure Analysis
  Reinspect, Retest
  Scrap and Rework - Fault of Vendor
  Discrepant Material Activity
  Downgrading

- **External Failures:** Costs generated by defective products being shipped to customers."

  Complaints
  Product or Customer Service
  Products Rejected and Returned/Returned Material Repair
  Warranty Replacement
  Marketing Error
  Engineering Error
  Factory or Installation Error

Appendix G

Selection of Industries

Appendix G

Selection of Industries

We believed, at the start of this study, that few, if any, companies would have the necessary data accessible in a form that would generate the quantitative answers on cost, resources, dates of investment, and so forth. The questions of this study cannot be answered on a company-wide basis or by any one person. The challenge therefore, was to find the information within a company and secure the company's cooperation to supply it. It was essential to the success of this study to have a commitment to the study and a willingness to cooperate from industry and individual company officials.

In order to find the companies and industries that would enable us to develop a meaningful analysis of investments in quality and measurement technologies, we developed the following criteria for targeting specific industries:

- The industry should have already made a relatively significant investment in quality enhancement.
- Individual companies within the industry should utilize QA&PC and measurement technologies at several different stages in the production process.

- The industry should offer the prospect of relatively good cooperation with NIST.[1]
- There should be a strong likelihood that a sufficient number of companies could provide data on investment and expenditures on QA and its measurement components.

Based on these criteria and discussions with the NIST COTR, we focused our data-collection efforts initially on two industries: optical fibers and analytic chemistry. NIST provided a list of contacts within the major firms in both industries.

Once the process of discussing the concept of the project was begun with the industry representatives, however, resistance to supplying quantitative information was encountered in both industries. Eventually, we discontinued the effort to develop data on the analytic chemistry industry and refocused on the semiconductor industry. The semiconductor industry was selected

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[1]The importance of good cooperation should be emphasized. In our proposal we noted: "Our previous experience in a number of industries...led us to believe that few, if any companies would have the data accessible in a form that would generate the quantitative answers on cost, resources, dates of investment and so forth..." We later went on to note that the success of the study "...will depend on the companies having the necessary information in a form compatible with our inquiries and on their willingness to supply it to us. Thus, it will be essential to have a commitment to the study and a willingness to cooperate from <u>both industry trade representatives and individual company officials</u>." Our concerns were proven to be warranted.

because QFA has strong relationships with key firms in the industry, and it was felt that this would help overcome any resistance to participation. At the same time, QFA identified a different set of contacts in the optical fibers industry and this aided, to a limited degree, the process of information collection for this industry.

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SUPPLEMENTARY NOTES

ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

Investment trends and overall industrial strategies for quality assurance are analyzed. Case studies of the semiconductor and optical fiber industries are undertaken. Data collection for the case studies is accomplished through analysis of the relevant literature and telephone and mail surveys. Industrial quality is defined in terms of its major components to allow more detailed analysis of the foci of corporate strategies and the shifts in these strategies over time. Adoption of individual components as part of corporate strategy is not related to company size but rather to commitment to competing successfully in global markets. International comparisons of strategies are made. The U.S. optical fiber industry invests relatively more in quality than do its foreign competitors, but the industry defines quality in a narrower, more traditional way compared to the semiconductor industry. The latter has adopted, in response to intense foreign competition, adopted a broader, systems view of quality similar to that of the Japanese. NIST is judged by respondents to play a significant role in providing measurement technology that is relevant for quality-related strategies.

KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

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